

Draft Technical Support Document for HWC MACT Standards

Volume I: Description of Source Categories

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Acronyms

AB	Afterburner
ACS	Acid scrubber
APCD	Air pollution control device
BIF	Boiler and Industrial Furnace
C	Cyclone
CAAA	Clean Air Act Amendments of 1990
CCS	Calvert collision scrubber
CKD	Cement kiln dust
CO	Carbon monoxide
DA	Dilution air
DI	Dry injection
DM	Demister
EDV	Electrodynamic venturi
EPA	U.S. Environmental Protection Agency
ESP	Electrostatic precipitator
FF	Fabric filter
FSI	Furnace sorbent injection
GC	Gas cooler
HAP	Hazardous air pollutant
HC	Hydrocarbons
HE	Heat exchanger
HES	High energy scrubber
HEPA	High efficiency particulate air filter
HS	Hydrogen chloride scrubber
HTHE	High temperature heat exchanger
HWC	Hazardous waste combustion
IWS	Ionizing wet scrubber
KOV	Knock out vessel
LTHE	Low temperature heat exchanger
LVM	Low-volatile metals
LWA	Lightweight aggregate
LWAK	Lightweight aggregate kiln
MACT	Maximum achievable control technology
PBC	Packed bed condenser
PCDD/PCDF	Polychlorinated dibenzofurans and dibenzo-p-dioxins
PIC	Product of incomplete combustion
POHC	Principal organic hazardous constituent
PM	Particulate matter
PTFE	Polytetrafluoroethylene
Q	Quench
QC	Quench column
RCRA	Resource Conservation and Recovery Act
S	Scrubber

SCA	Specific collection area
SDA	Spray dryer absorber
SVM	Semi-volatile metals
VQ	Venturi quench
VS	Venturi scrubber
TEQ	Dioxin/Furan Toxic Equivalency
WHB	Waste heat boiler
WS	Wet scrubber

1.0 Introduction

The United States Environmental Protection Agency is proposing “Maximum Achievable Control Technology” (MACT) standards for “hazardous air pollutants” (HAPs) for hazardous waste combustors. These include hazardous waste burning incinerators, cement kilns, lightweight aggregate kilns, boilers, and hydrochloric acid production furnaces. The MACT standards for the “Phase I” hazardous waste burning incinerators, cement kilns, and lightweight aggregate kilns will replace the interim standards promulgated for these sources on February 13 and 14, 2002 (67 FR 6792 and 67 FR 6968). The MACT standards for “Phase II” hazardous waste burning categories -- boilers and hydrochloric acid production furnaces – will be proposed (and promulgated) on the same schedule as the replacement Phase I standards.

This document provides:

Chapter 2 -- Process descriptions of each of the different source categories, including: hazardous waste incinerators, cement kilns, lightweight aggregate kilns, boilers, halogen acid furnaces, and sulfuric acid recovery furnaces.

Chapter 3 -- Descriptions of various air pollution control devices that are used to control the HAPs.

2.0 Process Descriptions

Combustion has developed as a means of treating various types of waste materials, including hazardous wastes, municipal wastes, medical wastes, and sewage sludges. Combustion is particularly effective for destroying hazardous organic wastes, reducing waste volume and mass, and producing a stable final waste form (ash or slag). Additionally, the heat generated from waste combustion may be used to produce electricity or process heat, or may be used to fuel industrial processes such as cement or lightweight aggregate production or industrial boilers.

Three important operating conditions for proper combustion are: (1) combustion temperature, (2) gas residence time at temperature, and (3) waste, supplemental fuel, and combustion air mixing and turbulence rates. These conditions vary with the chemical structure and physical form of the waste, as well as the combustor design.

Hazardous waste burning combustor classes include:

- Incinerators
- Cement kilns
- Lightweight aggregate kilns
- Boilers
- Halogen acid furnaces
- Sulfuric acid recovery furnaces.

Process components, characteristics, and important operating parameters are discussed for each of the different combustor classes.

2.1 Incinerators

Hazardous waste incinerators are used at both “commercial” and “on-site” (or captive) hazardous waste treatment facilities:

- Commercial facilities accept and treat wastes, for a tipping fee, which have been generated off-site. Commercial incinerators generate profit from treating hazardous wastes. There are approximately 22 commercial hazardous waste incineration facility sites run by 17 companies in the United States.
- On-site facilities treat wastes which have been generated at the facility to avoid the costs of off-site treatment. There are approximately 168 on-site hazardous waste incineration facilities in the United States.

Different types of technologies are used for hazardous waste incineration; the majority of which include rotary kilns, liquid injection incinerators, fluidized bed incinerators, and fixed hearth incinerators. The majority of the commercial incinerators are rotary kilns. Additionally, there are a few liquid injection, fluidized bed, and fixed hearth facilities. The on-site facilities

consist of approximately equal numbers of rotary kilns and liquid injection facilities, with a few fixed hearths and fluidized beds.

The following incinerator designs are discussed in this chapter: rotary kiln, fluidized bed, liquid injection, and fixed hearth. In general, these systems have common exhaust gas air pollution control requirements. Air pollution control devices and systems used on hazardous waste incinerators are discussed in the Chapter 2.1.5. Specific design, operating, and performance characteristics of the individual air pollution control devices are discussed in detail in Chapter 3.

2.1.1 Rotary Kiln Incinerators

Rotary kilns are the most commonly used technology for hazardous waste incineration. This is due to their ability to handle almost any conceivable waste form (e.g., bulk and containerized solids, sludges, slurries, bulk and containerized liquids, and less common wastes such as Department of Defense propellants, munitions, and nerve agents) as well as a variety of waste compositions (e.g., wide ranges of waste organics, halogens, heating values, and principal organic hazardous constituents (POHCs)).

Process Description

Rotary kiln systems used for hazardous waste incineration typically consist of two incineration chambers: a rotary kiln and an afterburner. A typical rotary kiln system is shown in Figure 2-1. The rotary kiln itself is a cylindrical refractory-lined steel shell typically with a diameter which is typically less than 15 to 20 feet (to allow for truck or rail shipment) and a length-to-diameter ratio of 2:1 to 10:1. The shell is supported by two or more steel trundles that ride on rollers, allowing the kiln to rotate around its horizontal axis. The refractory is typically made of an acid resisting brick. Rotary kiln incinerators are typically sized around 60 million Btu/hr, but may be as large as 150 million Btu/hr.

The inside of the kiln is usually lined with a smooth refractory; although recent designs have included internal vanes or paddles to encourage solids mixing along the kiln length. The kiln is oriented on a slight incline from the horizontal, known as the “rake”. The rake is less than 5° and typically ranges from 2 to 4°. The kiln rotation rate typically ranges from 0.5 to 2 rotations per minute. Mixing may be improved by increased rotation rate; however, this also acts to reduce solids residence time. Kiln rotation and incline serve to promote the mixing of wastes with combustion air, as well as to facilitate the heat transfer between the waste and hot flames and refractory, and to move the wastes through the rotary section.

Almost all hazardous waste rotary kiln incinerators are of the “co-current” design because they are better suited toward treating combustible solid wastes. In the co-current design, shown in Figure 2-1, wastes and auxiliary fuels are fed at the same upper kiln end (i.e., the waste and flue gas travel in the same direction). Co-current designs provide for rapid ignition of the cold wastes and maximum gas residence time for the products of combustion and thus achieve the highest degree of volatile organic destruction in the rotary section.

Solid and liquid wastes are fed directly into the rotary kiln. Solids can be fed, on a continuous or semi-continuous basis, through a variety of waste feed mechanisms such as a ram feeder, auger screw feeder, or belt feeder for waste contained in drums. For batch feeding, an air lock is usually used to reduce the amount of air infiltration through the feeding chute. Liquid wastes may also be injected, with pressure, steam, or air assisted atomizing nozzles, directly into the kiln through the main burner. These liquid wastes may also be injected through a waste lance, and/or mixed with the solid wastes. In most cases, rotary kilns can handle unprocessed wastes. However, waste pretreatment may include mixing of liquid and solid wastes, as well as neutralizing corrosive wastes prior to being fed to the kiln. Waste grinding and sizing may aid in smooth kiln operation.

Wastes are heated by the primary flame, bulk gases, and refractory walls. Through a series of volatilization and partial combustion reactions, combustible fractions of the wastes are gasified. The solids continue to heat and burn as they travel down the kiln. Typically, solids retention time in the kiln is 0.5 to 1.5 hours, while gas residence time through the kiln is usually around 2 seconds. Waste feed to the kiln is controlled so that the waste contributes no more than 20% of the kiln volume. Flame/solids temperatures in the rotary kiln range from 1,200 to 3,000°F.

An auxiliary gas or oil burner, located at the feeding end of the kiln, is used for start-up (to bring the unit up to temperature) and to maintain desired kiln temperature when sufficient heat input is not available from the waste. Wastes with an average heating value of 4,500 Btu/lb are typically adequate to sustain combustion at kiln temperatures between 1,600 to 1,800°F. Combustion air is provided through ports on the face of the kiln, as well as through rotary seal leakage. The kiln typically operates at 50 to 200% excess air levels.

Kiln operating pressure is maintained at negative to the atmosphere, typically -0.5 to -2.0 in. H₂O gauge, through the use of an induced draft fan which is located downstream of the air pollution control system. Operation at negative pressure assures that fugitive emissions of combustion gases to the atmosphere through rotary seal leaks are avoided. Seals on the ends of the rotary section provide possible kiln gas leakage points. There is potential for kiln gas fugitives to escape through leaks in rotary seals when excessive kiln pressure develops. This “over-pressure” can occur when highly combustible or explosive wastes are fed into the kiln. The resulting increase in combustion gas volume cannot be handled by the downstream exhaust system, creating an over-pressure in the kiln. Also, if seals become worn or damaged, ambient air infiltration through them may make it difficult to maintain temperature at an acceptable kiln gas flow rate.

Overcharging of highly combustible or explosive wastes may also lead to kiln “puffing”. Volatiles are released quickly at high temperature thus depleting local oxygen, creating pyrolysis conditions and the formation of products of incomplete combustion (PICs). Higher rotations rates also increase the puff magnitude because devolatilization rates are enhanced by bed mixing. Puffing can be avoided by operating with smaller batch sizes or lower charging rates to reduce the hydrocarbon release rate to avoid consuming available oxygen. Also, transient puffs can be minimized by operating at lower rotational speeds and lower kiln temperatures.

To avoid over-pressurization caused by feeding highly combustible wastes, a thermal emergency relief vent, typically located between the afterburner and the air pollution control system, is used to protect the equipment. Flue gases are released through this vent when over-pressurizations occur. The use of the emergency relief vent is minimized to avoid the direct release of untreated flue gases to the atmosphere (i.e., flue gases which have not passed through the air pollution control system).

Inorganics, ash, slag, and other incombustible items that remain when the waste reaches the end of the kiln fall into an ash pit. Typically, the ash is first water quenched, and dropped into a water trough that seals the kiln. Dry collection systems allow for undesirable air leakage into the kiln. Dropping of hot solids into the water seal trough can result in steam explosions, often leading to positive pressure excursions.

Exhaust gas from the kiln is usually routed to a secondary refractory lined combustion chamber, referred to as an “afterburner”. The afterburner is typically operated at about 2,000 to 2,500°F, with 50 to 150% excess air, turbulent mixing flow, and a gas residence time from 1 to 3 seconds to ensure complete combustion of the remaining volatile gas phase unburned components in the kiln flue gas. An auxiliary fuel, and sometimes pumpable liquid hazardous wastes, are used to maintain the afterburner temperature. A hot cyclone may be positioned between the kiln and afterburner for removal of entrained solid particles that may cause slagging problems in the afterburner.

Design modifications to the rotary kiln have included: (1) a “fast” rotary kiln which rotates at a rate greater than 20 rotations per minute to provide efficient mixing; (2) starved air and oxygen assisted kilns to reduce flue gas volume and auxiliary fuel requirements; and (3) “slagging” kilns. The slagging kiln operates above the ash melting point (2,600 to 2,800°F) to generate a molten ash. Eutectic properties of slag are controlled using additives to the feed. Slagging kilns typically have a negative rake, permitting for the accumulation of slag in the kiln. In addition, these kilns have the ability to accept metal drums and salt laden wastes, provide better destruction efficiency and generate lower particulate emissions compared with normal rotary kilns, and produce a slag product known as “frit” which is less leachable than non-slagging kiln ash. However, slagging kilns have increased NO_x emissions, shorter refractory lifetime, and potential for the slag to solidify in the kiln, creating operational difficulties.

Operating Parameters

Operating parameters which are important to rotary kiln operation include:

- Kiln and afterburner exit temperature -- The kiln temperature is typically maintained above 1,500°F; and afterburner temperature above 2,000°F. Temperature must be maintained above the minimum demonstrated for adequate destruction of POHCs and avoidance of PICs. Monitoring limitations include errors in measurement from furnace and flame radiation. The temperature may be controlled through adjustment of waste, auxiliary fuel, and combustion air feed rates.

- Kiln pressure -- Kiln pressure must be maintained at negative to atmosphere and the afterburner pressure must be below that of kiln to prevent kiln fugitive emissions through kiln rotary seals. Pressure is controlled by use of an induced draft fan and damper system downstream of the combustion chambers.
- Combustion gas velocity (flowrate) -- This is controlled to ensure proper combustion gas residence time at operating temperature for complete destruction of volatile PICs. Gas flowrate is dependent on combustion air rate, waste feed composition and feed rate, and auxiliary fuel type and feedrate.
- Waste feed rate -- This is adjusted to avoid over-loading, over-pressuring, and depleting kiln oxygen, which may result in kiln fugitives and excessive kiln flue gas volatiles. If the kiln is fed semi-continuously, the maximum size of each batch must be controlled.
- Oxygen concentration at kiln and afterburner exit -- This is controlled to assure availability of oxygen, and thus the potential for complete combustion (i.e., lower CO, HC, and PIC levels). The kiln is typically operated at 50 to 100% excess air, while the afterburner is typically operated at 100 to 200% excess air.
- CO and HC combustion gas levels -- CO and HC levels are monitored to ensure satisfactory operation of the kiln and afterburner to achieve complete combustion and avoidance of PIC formation.
- Kiln solids residence time -- This is typically maintained at 0.5 and 1.5 hours and is controlled by rotation rate and kiln rake to ensure that the waste spends sufficient time in the kiln to be thoroughly treated. Controlling residence time is important for treatment of relatively non-combustible wastes.
- Kiln solids and combustion air mixing -- This assures that volatiles are thoroughly combusted. This is controlled by maintaining an adequate kiln rotation rate.

2.1.2 Liquid Injection Incinerators

Liquid injection incinerators, like rotary kiln incinerators, are commonly used for hazardous waste incineration. Liquid injection incinerators can be used to dispose of virtually any combustible liquid or liquid-like waste (e.g., liquids, slurries, and sludges).

Typical liquid injection incinerator systems, which are possibly the simplest type of combustion device, include a waste burner system, an auxiliary fuel system, an air supply system, a combustion chamber, and an air pollution control system. A typical liquid injection incinerator is shown in Figure 2-2. Liquid wastes are fed and atomized into the combustion chamber through the waste burner nozzles. These nozzles atomize the waste and mix it with combustion air. Atomization is usually achieved either by mechanical methods such as a rotary cup or pressure atomization systems, or by twin-fluid nozzles which use high-pressure air or steam. With a relatively large surface area, the atomized particles vaporize quickly, forming a highly

combustible mix of waste fumes and combustion air. This mixture ignites and burns in the combustion chamber. Typical combustion chamber residence time and temperature ranges are 0.5 to 2 seconds and 1,300 to 3,000°F, respectively, in order to ensure complete liquid waste combustion. Liquid waste feed rates can be over 500 gal/hr. If the energy content of the waste is not high enough to maintain adequate ignition and incineration temperatures, a supplemental fuel such as fuel oil or natural gas is provided. In some cases, wastes with high solids are filtered prior to incineration to avoid nozzle plugging.

The liquid injection incinerator may handle aqueous or non-aqueous wastes with viscosity less than 10,000 SSU by directly atomizing the waste through a burner nozzle. The waste must be atomized to small droplets, typically of 40 µm or less. Atomization is usually accomplished mechanically using rotary cup or pressure atomization systems. Wastes with high solids are filtered prior to entering the feed tank. The liquid waste fuel system transfers the waste from drums into a feed tank.

The combustion chamber can be as simple in design as a refractory-lined cylinder, or it can be relatively complex with combustion air preheat around the chamber and the ability to fire multiple fuel streams. The incinerator can be designed using either a horizontal or vertical orientation. In either case, flame impingement on the combustion chamber wall is undesirable because it can lead to refractory corrosion and loss of heat. Thus, the burner(s) are located to prevent flame impingement on the walls.

2.1.3 Fluidized Bed Incinerators

Fluidized beds are occasionally used for hazardous waste combustion, although not nearly as frequently as rotary kilns or liquid injection types.

Process Description

A fluidized bed incinerator consists of a fluidized bed reactor, fluidizing air blower, waste feed system, auxiliary fuel feed system, and an air pollution control device system. A typical reactor is shown in Figure 2-3. The fluidized bed reactor is usually a vertical cylindrical vessel containing a bed of granular material (typically sand or some other inert material) at the bottom. Combustion air is introduced at the bottom of the vessel and flows up through openings in a distribution plate. The distribution plate is designed to allow sufficient air to pass upward into the bed but to prevent bed media from falling through when the bed is at rest. The air flows up through the bed material, suspending the granular particles.

Solid, liquid, and gaseous waste fuels may be injected into the bed, where they mix with the combustion air and hot bed media, and burn. The waste is put in direct contact with the bed media, causing heat transfer from the bed particles. At the proper temperature, waste ignition and combustion occur. The bed media acts to scrub the waste particles, exposing fresh surface by the abrasion process which encourages rapid combustion of the waste. Waste and auxiliary fuel are injected radially into the bed and react at temperatures from 840 to 1,500°F. Further reaction occurs in the volume above the bed, known as the “freeboard”, which is maintained at

temperatures up to 1,800°F. An auxiliary burner is located above the bed to provide heat for start-up, reheat, and maintenance of bed temperature. Waste ash and bed materials are removed periodically from the bottom of the bed. Finer particles of waste ash and ground-down bed materials are entrained out of the bed with the exhaust gas.

Generally, fluidized bed incinerators have two separate waste preparation/feed systems -- one for solids and one for liquids. In some cases, four feed systems are employed: wet solids, dry solids, viscous fluids, and non-viscous fluids. Solid wastes are usually fed into a coarse shredder. The coarsely shredded waste falls into a classifier which separates the light and dense particles. The lighter particles are transferred to a secondary shredder from which they are conveyed to the hopper for feeding the fluidized bed. Liquid waste is pumped into a larger holding tank. To ensure the mixture is as homogeneous as possible, the liquid waste is continuously pumped through a recirculating loop from the bottom of the tank to the top. A metering pump draws the waste fuel to be burned from the tank to the primary reactor. Nozzles are used to atomize and distribute the liquid waste within the bed.

Due to efficient mixing, fluidized beds in general can operate at lower temperatures compared with other incineration technologies. This potentially results in lower NO_x and semi-volatile metals emissions, as well as lower potential for ash agglomeration and lower auxiliary fuel requirements. This also allows for the treatment of low heating value wastes (below 4500 Btu/lb). The use of alkali-containing bed materials such as lime or sodium allows for “in-situ” acid gas control; hence, fluidized beds may be efficient at treating high sulfur or halogenated wastes due to reduced downstream acid gas emissions control requirements.

Maintaining proper bed fluidization is important for effective waste treatment. Solid waste size reduction (shredding or grinding) may be required. Fluid beds are not well suited for irregular, bulky wastes, tarry solids, or wastes with a fusible ash content. Improper bed fluidization may lead to bubbles of gas that “short circuit” the bed, allowing for potentially unburned wastes to escape the bed. Particulate emissions in the flue gas may be high compared to other incinerator designs due to the high fluidization velocity, erosion of bed material, bed turbulence, and the small size of waste and bed particles.

Operating Parameters

Fluidized bed operating parameters include:

- Bed temperature -- The fluidized bed temperature must be monitored and controlled by waste feed and auxiliary burner adjustments, as well as adjustments of the input rate of combustion air and inert fluidizing gases, to assure that the temperature remains above an established minimum. Operating temperatures are normally maintained in the 1,400 to 1,600°F range. Because of the large thermal mass of the bed, bed temperature changes slowly.
- Oxygen level -- The oxygen level in the bed must be maintained to ensure the potential for complete combustion.

- CO and HC flue gas levels -- Monitoring the CO and HC concentrations in the flue gas is also an indication of complete combustion.
- Bed retention time -- Solids retention time in the bed is a measure of the thorough treatment of the waste. Retention time may be important for relatively non-combustible wastes.
- Bed fluidization -- Uniform bed fluidization must be maintained to properly treat the waste.
- Bed gas residence time -- The combustion gas residence time must be monitored to assure that the combustion gas has been exposed to volatile destruction temperature for a sufficient period of time.

2.1.4 Fixed Hearth Incinerators

Fixed hearth incinerators, which are used extensively for medical waste incineration, are less commonly used to incinerate hazardous wastes. Fixed hearths can handle bulk solids and liquids, however, this design does not have the versatility of a rotary kiln.

Process Description

Fixed hearth incinerators typically contain two furnace chambers: a primary and secondary chamber. A typical fixed hearth system is shown in Figure 2-4. Solid and liquid wastes may be charged into the primary chamber. Small units are normally batch-fed, while larger units may be continuously fed with a screw feeder or moving grate, or semi-continuously fed with a ram pusher. In some designs, there may be two or three step hearths on which the ash and waste are pushed with rams through the system. In other designs, rotating rabble arms stir the solid waste material on the grate.

A controlled flow of “under-fire” combustion air is introduced, usually up through the hearth on which the waste sits. In some designs, combustion air may also be provided from the wall over the waste bed. In many fixed hearth incinerators, known as controlled air or starved air incinerators, 70 to 80% of the stoichiometric air required is provided in the primary chamber, thus the primary chamber is operated in a “starved-air” mode. In this situation the waste is pyrolyzed and partially combusted. In some cases steam injection into the primary combustor is used to enhance waste fixed carbon burnout (fixed carbon is non-volatile carbon which will burn only when exposed to combustion air). Because fixed hearth incinerators have relatively poor mixing of waste with the combustion air, they are not effective at processing wastes which require turbulence for effective combustion, such as powdered carbon, pulp wastes, sludges, and viscous wastes.

Primary chamber temperature is controlled by the under-fire air supply. Temperature in the primary chamber is maintained high enough to destroy hazardous organics in the waste (typically 1,000°F) but low enough to reduce the potential for slagging and refractory damage

(1,800°F). Waste slagging may clog the under-fire air ports. Bottom ash is removed on a continuous or semi-continuous basis, depending on the unit design. The ash is usually dumped into a water bath, which provides a seal between the primary unit and the atmosphere.

For controlled air units, due to insufficient supply of air, the primary chamber flue gas will contain unburned hydrocarbons, and high levels of CO and H₂. These volatiles are burned out in a secondary or afterburner chamber. In the secondary chamber, 140 to 200% excess air is provided, as well as sufficient residence time at temperature for complete volatiles burnout. Liquid wastes may be injected either in the primary or secondary chamber. Supplementary fuel may be provided in both chambers for the maintenance of temperature. Secondary chamber temperature may be as high as 2,000°F. Temperatures beyond this are avoided to prevent refractory damage, decreased gas residence time, and usage of auxiliary fuel.

Operating Parameters

Important fixed hearth operating parameters include primary chamber and afterburner temperature. Primary chamber temperature is controlled by the under-fire air supply. Afterburner temperature can be controlled by auxiliary fuel firing and primary waste feed rate adjustments. Note that the capacity of the afterburner or secondary chamber limits the primary chamber burning rate. The afterburner must have adequate volume to accept and oxidize all volatile gases generated in the primary chamber. Additionally, the afterburner must be kept operating at excess air conditions to ensure complete volatile burnout.

2.1.5 Air Pollution Control Techniques

The exhaust combustion gas leaving the primary (or secondary if used) incinerator combustion chamber will be composed primarily of CO₂, O₂, N₂, and H₂O vapor. It may also contain undesirable constituents that are byproducts of the combustion process such as: (1) acid gases (HCl, HF, SO₂, and NO_x); (2) entrained suspended solid particles (potentially containing condensed metals and unburned non-volatile organics); (3) inorganic vapors (e.g., volatile metals such as mercury); and (4) products of incomplete combustion (PICs) such as unburned organics and CO. Levels of these combustion byproducts are highly site specific, and depend on a variety of factors such as waste composition, and incinerator system design and operating parameters (e.g., temperature and exhaust gas velocity).

Most hazardous waste incinerators use air pollution control systems to remove undesirable components such as suspended solid particles (“particulate matter”) and acid gases from the exhaust gas prior to release to the atmosphere. The air pollution control system is typically made up of a series of different devices that work as a unit to clean the exhaust combustion gas. Unit operations usually include exhaust gas cooling, followed by particulate matter and acid gas control.

Exhaust gas cooling can be performed many different ways including using a waste heat boiler or heat exchanger, mixing with cool ambient air, or injecting water into the exhaust gas. For particulate matter (PM) and acid gas control, many different types of air pollution control

devices can be used, including wet scrubbers (such as venturi and packed bed type wet scrubbers, ionizing wet scrubbers (IWSs)), electrostatic precipitators (ESPs), and fabric filters (FFs) (sometimes used in combination with dry acid gas scrubbing). In general, the control systems can be grouped into the following three categories: “wet”, “dry”, and “hybrid wet/dry” systems.

In wet systems, a wet scrubber is used for both particulate and acid gas control. Typically, a venturi scrubber and packed bed scrubber are used in a back-to-back arrangement. Ionizing wet scrubbers, wet ESPs, and innovative venturi-type scrubbers may be used for more efficient particulate control. Wet systems generate a wet effluent liquid waste stream (scrubber blowdown), are relatively inefficient at fine particulate control compared to dry control techniques, and have equipment corrosion concerns. However, wet scrubbers typically provide efficient control of acid gases and have lower operating temperatures (compared with dry systems) which may help control the emissions of volatile metals.

In dry systems, a FF or ESP is used for particulate control, sometimes in combination with dry scrubbing for acid gas control. Dry scrubbing systems in comparison with wet scrubbing systems are less efficient for control of acid gases.

In hybrid systems, a dry technique (ESP or FF) is used for PM control (and possibly acid gas control with use of dry scrubbing) followed by a wet technique (venturi and packed bed scrubber) for acid gas control. Hybrid systems have the advantages of both wet and dry systems (lower operating temperature for capture of volatile metals, efficient collection of fine PM, efficient capture of acid gases), while avoiding many of the individual disadvantages. In some hybrid systems, known as “zero discharge systems”, the wet scrubber liquid is used in the dry scrubbing operation, thus minimizing the amount of liquid byproduct waste. Such systems are less effective for volatile metals control.

In a separate and unique category are facilities which do not use any air pollution control devices. Some liquid injection and fixed hearth facilities, which generate low PM levels when treating low ash content wastes, and/or may not generate acid gases when burning non-halogen containing wastes, do not utilize post-combustion air pollution control devices.

2.2 Cement Kilns

The manufacture of cement is one of the largest mineral production processes in the United States. There are roughly 110 plants in the United States that produce about 80 million tons of cement. There are about 15 sites where cement kilns are burning hazardous waste derived fuel in the United States.

2.2.1 Process Components

Cement is made from a carefully proportioned mixture of raw materials containing calcium (typically limestone, although oyster shells and chalk may also be used), silica and alumina (typically clay, shale, slate, and/or sand), and iron (typically steel mill scale or iron ore). These materials are ground to a fine power (80% passing 200 mesh), thoroughly mixed, and

heated to a very high temperature to produce a cement “clinker” product. The raw feed material, known as “meal”, is heated in a kiln, a large, inclined, rotating cylindrical steel furnace lined with refractory materials. Heating of the meal as it moves through the kiln drives a number of chemical and physical processes which are necessary to form the clinker. In the first “drying and preheating zone”, occurring in a temperature range of 70 to 1,100°F, residual water is evaporated from the raw meal feed, and clay materials begin to decompose and are dehydrated (removing bound water). Next, in the “calcining zone” (with materials temperatures ranging from 1,100 to 1,650°F) the material is “calcined”; that is calcium carbonate in the limestone is dissociated producing calcium oxide (“burnt lime”) and carbon dioxide. Finally, in the “burning zone”, also known as the “clinkering” or “sintering” zone, calcium oxide reacts with silicates, iron, and aluminum to form “clinker”. The clinker is a chemically complex mixture of calcium silicates, aluminates, and aluminoferrites. A minimum meal temperature of 2,700°F is necessary in the burning zone of the kiln to produce the clinker.

Heating of the raw meal to produce cement clinker can take place in three different types of arrangements: “wet”, “dry”, or “semi-dry” processes. The hardware used to dry, calcine, and clinker the raw meal is the difference between the three set-ups; the physical and chemical processes to produce the cement are similar. A rotary kiln is the common element in all systems, and the kiln always contains the burning zone and all or part of the calcining zone.

Wet Process Kilns

A schematic of the wet cement making process is shown in Figure 2-5. In wet process kilns, ground raw materials are mixed with water (about 30% by weight) to form a slurried meal. The slurry is ground in wet mills to the required size and pump fed to the elevated end of the rotary cement kiln. The slurry is fed to the kiln through a flow metered pump. The kiln is a long (450 to 750 ft.) inclined rotating cylindrical steel furnace, with a length-to-diameter ratio of about 30:1 to 40:1. Refractory material internally lines the kiln to protect the steel shell from the high temperature and to retain heat within the kiln. The kiln slope (3 to 6°) and rotation (50 to 70 revolutions per hour) cause the meal to move toward the “hot” lower end of the kiln. The kiln is fired at the hot end, usually with coal or petroleum coke as the primary fuel; natural gas, fuel oil, or hazardous waste derived fuel may also be used as a supplemental energy source. This energy is required to heat the raw materials to clinker formation temperature. As the raw meal moves down the kiln it is heated by hot fuel combustion gases moving in a “counter-current” direction. This configuration (exhaust gases and solids flowing in opposite directions through the kiln) provides for more efficient heat transfer compared with “co-current” operations. Kiln rotational speed, raw meal feed, and fuel firing rates are adjusted to maintain clinker quality and heat transfer and to limit the raw meal from occupying more than 15 to 20% of the internal kiln volume. To improve the energy efficiency of the process, steel chains are typically attached to the inside of the kiln shell in the upper kiln drying zone. The chains act as a heat transfer mechanism. As the kiln rotates, the chains hang by gravity and pick up heat from the kiln flue gases. When the hot chains settle back into the meal after further rotation, heat is transferred from the chains to the meal.

The wet cement making process is the older traditional process, characterized in part by handling, mixing, and blending of the raw materials in the slurry form, and lower emissions of kiln dust. However, because all water must be evaporated out of the slurry mixture, wet process kilns require greater energy input than other types of cement kilns; typically, from 5 to 7 million Btu/ton of clinker product is required. Despite the inefficiency, in situations where the raw materials are quarried in a wet form, the wet process may be preferred.

A typical solids and gas temperature profile of a wet kiln is shown in Figure 2-6. The feed does not begin to heat up until all of the water in the raw meal slurry is evaporated. The gas temperature in the burning zone approaches 4,000°F, while the clinker reaches a maximum temperature of approximately 2,700°F, which is required for the formation of clinker. Flue gas velocity is also shown in Figure 2-7 as a function of kiln axial location. This relates to a kiln gas residence time of over 10 seconds. Typical solids residence time in the kiln is from 2 to 3 hours.

Dry Process Kilns

Due to higher energy efficiency compared with wet kilns (3.4 to 4.5 million Btu/ton clinker), and improvements in dry grinding and blending technology, dry processes have become popular. In the dry process, the ground raw material is dried and pneumatically transported to the kiln, or preheater if used. Kiln exhaust flue gases or hot clinker cooler air are typically used for drying the raw materials. There are three different dry process configurations: long, preheater, or preheater/precalciner.

Long Dry Process Kilns -- A long dry process kiln has a same configuration as the wet type; the only difference is that raw meal is fed in a dry form. Long dry kilns have typical length-to-diameter ratios of about 30:1. They are typically shorter than wet kilns since slurried meal water evaporation is not required, allowing for the meal to be heated more rapidly. A typical long dry kiln solid/gas temperature profile is shown in Figure 2-8. Kiln gas and solids residence times are similar to those of wet kilns (on the order of 10 seconds and 2 to 3 hours respectively). Internal chains are also used in dry process long kilns (similar to wet kilns) to increase process energy efficiency.

Preheater Dry Process Kiln -- The preheater arrangement process is shown in Figure 2-9. Preheaters are used to further increase the thermal efficiency of the cement making process. In the preheater system, kiln exhaust gas is used to increase meal temperature and partially calcine the meal before feeding it to the rotary kiln. The preheater accomplishes the same tasks as the back end of a long kiln, but with greater energy efficiency than the rotary kiln. There are two types of preheater arrangements: the traveling grate type, and more commonly, the suspension type. A suspension preheater ("Humboldt" Design) consists of a vertical tower containing a series of cyclone-type vessels (typically containing four stages). Raw meal is introduced at the top of the tower. Hot kiln exhaust flue gases pass counter-current through the downward moving meal to heat the meal prior to introduction into the kiln. The cyclones are used to separate the meal from the kiln flue gases; collected meal in the cyclones is sequentially dropped into the next lower stages. Because the meal enters the kiln at a higher temperature than that of the

conventional long dry kilns, the length of the pre-heater kiln is shorter; kilns with preheaters typically have length-to-diameter ratios of about 15:1.

A typical solid/gas temperature profile is shown in Figure 2-10. The preheater kiln typically has a gas residence time of about 6 seconds and a solids residence time of about 30 minutes. The gas residence time through the preheater cyclones (typically four stages) is usually about 5 seconds. Figure 2-11 shows typical gas velocities through the preheater kiln system.

With preheater systems, it is often necessary to utilize an “alkali” bypass, in which a portion of the kiln flue gases are routed away from the preheater tower at a location between the feed end of the rotary kiln and the preheater tower. The bypass is used to remove undesirable components, such as certain alkali constituents, that may accumulate in the kiln due to an internal circulation loop caused by volatilization at high temperatures in the kiln and condensation in the lower temperatures of the preheater. Accumulated alkali salts may cause preheater operating problems such as clogging of the cyclones, and an increase in fine NaCl or KCl fume in the emissions gases. Typically 10 to 15% of the flue gas is routed through the bypass. Semivolatile metals, which have vaporization behavior similar to alkali salts, tend to also be more concentrated in the bypass gas. Systems without bypasses are limited with respect to raw meal and waste concentrations of alkali metals, chloride (greater than 0.015% Cl by weight), and sulfur that can be tolerated.

The internal circulation of alkali components is greater in systems with preheaters compared to systems without preheaters due to the filtering effect of feed material flow in the preheater cyclones. Systems without preheaters have a kiln dust with a high content of alkali salts, which can be removed from the internal cycle when caught in the air pollution control device. However, for the preheater arrangement, to reduce the alkali buildup, a bypass is required.

Preheater/Precalciner Dry Process Kiln -- A preheater/precalfiner process is also shown in Figure 2-9. A preheater/precalfiner is similar to the preheater arrangement described above with the addition of an auxiliary firing system to further increase the raw materials temperature prior to introduction into the kiln. An additional precalfiner combustion vessel is added to bottom of preheater tower, immediately upstream of the kiln. Typical systems use 30 to 60% of the kiln fuel in the precalfiner to release up to 95% of the CO₂ from the raw material. Precalfiner air can be supplied either directly with the precalfiner fuel, or else supplied at hot end of the kiln. In another arrangement, the kiln flue gas may be routed around the calciner directly to the preheater. Kilns with preheater/precalfiners can be even shorter than those with preheaters only (length-to-diameter ratio of 10:1).

The primary advantage of using the precalfiner is to increase the production capacity of the kiln, because only the clinker burning is performed in the kiln. The use of the precalfiner also increases the kiln refractory lifetime due to reduced thermal load in the burning zone. These configurations also require a bypass system for alkali control.

A typical solid/gas temperature profile of a kiln with a preheater and precalciner is shown in Figure 2-12. It is similar to that of the preheater kiln; however, the time at which the gas temperature is above 1,650°F is slightly less in a precalciner type kiln.

Semi-Dry Process Kilns

In the semi-dry process, the ground feed material is pelletized with 12 to 14% water. The pellets are put on a moving “Lepol” grate on which they are dried and partially calcined by hot kiln exhaust gases before being fed to the rotary kiln. A semi-dry process schematic is shown in Figure 2-13. A typical solids/gas temperature diagram is given in Figure 2-14.

2.2.2 Clinker Handling

In all arrangements, the clinker is removed from the kiln at the hot end. After it passes through the burning zone and by the kiln flame, it enters a short cooling area where the clinker melt begins to solidify; the cooling rate from the burning zone to the kiln exit is important because it determines the microstructure of the clinker. The clinker leaves the kiln at about 2,000°F and falls into a clinker cooler. The cooler is typically a moving grate on which the clinker sits. Cooling air is blown through the clinker bed. The cooled clinker consists of grey colored nodules of variable diameters, typically up to two inches. The clinker is blended with gypsum and ground in a ball mill to produce the final product, cement. Hot exhaust air produced from the clinker cooler is either directed to the kiln where it is used as combustion air or used to pre-dry the raw feed material in the case of dry process kilns.

2.2.3 Hazardous Waste Feeding Techniques

The feeding of the hazardous waste into the kiln is a primary factor in determining the destruction of the waste (which is dependent on temperature and residence time). The method of introducing the waste also depends on its physical state, as discussed in the following sections.

Liquid wastes are either blended directly with the conventional fuels which are provided at the hot end of the kiln, or they are injected separately through a separate burner/atomizer into the primary kiln flame. Extreme combustion conditions of high temperature (greater than 3,000°F), turbulent mixing, and long as phase residence time (from 4 to as high as 16 seconds in long kilns) have been demonstrated to overcome any possible deficiencies in local oxygen availability and potential atomization problems.

In the past, solid wastes were fed at the cold end of the kiln with the raw meal. However, the addition of wastes at the cold end is no longer practiced because, as the wastes move down the kiln and get hotter, volatile components are driven off at temperatures below those required for complete oxidation and destruction. Note that the current Boiler and Industrial Furnaces (BIF) Rule no longer allows this, requiring that at the location of solid waste feeding, the combustion gas temperature must exceed 1,800°F and that adequate oxygen must be present to ensure complete combustion of organic constituents in the waste. Thus, significant emissions of

unburned volatiles may occur without the use of an afterburner or other add-on volatile emissions control techniques.

Neither are solid wastes usually charged directly into the hot end burning zone for a variety of reasons. If introduced too close to the end of the kiln, the solid wastes may leave the kiln with the clinker in an unburned state due to insufficient time in the hot conditions. Their presence can create local reducing conditions which adversely effect clinker quality such as strength, stability, set-up time, and color. Oxidizing conditions must be maintained in the burning zone. If insufficient oxygen is present, a key component of cement clinker, tetra calcium aluminoferrite does not form; instead Fe_2O_3 is reduced to FeO . This leads to a clinker product that produces a quick setting cement with decreased final strength. Additionally, the presence of unburned carbon in the burning region produces a clinker with an undesirable brown color. To overcome these feeding location limitations, a variety of techniques are used for the introduction of solid wastes into cement kilns. The choice depends on the solid waste type (composition and physical attributes) and kiln configuration (dry long, dry with preheater, wet, etc.).

Methods which are used rely on the introduction of the solid waste into the calcining zone. For long kilns, this means that the waste is introduced mid-kiln, while for preheater/precalciner kilns, it is introduced onto the feed shelf. Introduction in the calcining zone allows the solids to have sufficient residence time for the organics to be driven off so that the presence of waste combustibles do not reach the burning zone creating reducing conditions which are detrimental to clinker quality, and yet far enough away from the cold end to provide sufficient temperature and residence time for complete destruction of volatile gaseous organics. These methods include:

- For long type wet and dry kilns, and dry kilns with preheaters, a method has been developed for charging solid wastes directly through a hatch on the rotating kiln wall at an intermediate location within the calcining zone. At each rotation, the hatch is opened, and containerized waste solids are fed down a drop tube that is inserted through the hatch and into the rotating kiln. The drop tube prevents hot mineral material from escaping through the port or contacting the enclosure. It is important that the volume of the volatile components does not exceed the capacity for their complete combustion in the gas stream. Thus, wastes are containerized in discrete quantities to minimize the potential for overloading the combustion capacity and create local reducing conditions.
- As mentioned, for preheater or precalcining kilns, the solid waste may be injected directly into the precalciner vessel or preheater inlet.
- Containerized solid wastes may also be injected at the hot end of the kiln at high enough velocity so that they are projected into the calcining zone. An “air cannon”, which is mounted to the kiln hood, is used to propel the waste containers.

Other methods used for solid waste treatment in cement kilns can be used. If the waste is in powdered form, it may injected directly into the primary burning zone coal flame of the cement kiln. In another set up, solid waste is burned in a separate kiln or combustor; the flue gas

is routed to the hot end of the cement kiln, which is used as an afterburner and for acid gas control.

2.2.4 Air Pollution Control System

Kiln combustion gases are drawn through the system with an induced draft fan; this maintains kiln pressure under atmospheric to prevent fugitive emissions. Kiln (or preheater if used) exhaust gases contain large amounts of suspended fine solid particles due to the turbulence in the kiln from the rotary action and from the use of finely ground feed material. These entrained particles are known as “cement kiln dust” (CKD). The CKD is composed of fuel and waste ash and meal raw materials. The CKD is removed from the exhaust gas in either ESPs or FFs. Electrostatic precipitators have been the more common choice due to their reliability and low maintenance requirements. Recently though, with increasingly strict particulate control standards, FFs have also become common. Typically, FFs are more efficient at collection of submicron particulate and provide lower guaranteed particulate matter emissions levels. Electrostatic precipitators are more common on wet kilns since the higher exhaust gas moisture content is difficult for FFs to handle. Fabric filters are more common at dry process kilns. Depending on the facility, the kiln exit gas may need to be cooled prior to being introduced into the air pollution control device. Air dilution or water spray may be used for this purpose. In another arrangement, hot gases leaving the kiln are cooled in a waste heat boiler which produces steam; the steam is converted to electricity that is used on-site. Many plants return a portion of the collected CKD to the raw feed materials or directly into the hot end flame (known as “insufflation”). However, some must be removed to lower the buildup of alkali salts. Cement kiln dust can be used in other industries as neutralizers or additives, however, usually the excess CKD is land disposed.

Due to the nature of the cement process, add-on acid gas air pollution control devices, such as wet or dry scrubbers, are not used. The cement feed raw materials are high in alkaline content (limestone in particular), which provides for “in-situ” absorption of chlorine and other halogens and sulfur (which may originate in either the coal or the hazardous waste), preventing the formation and release of acid gases to a large degree.

CO and HC main stack gas emissions levels from cement kilns are typically higher than those encountered in hazardous waste incinerators. CO has been suggested to be high due to the limestone calcination process and the decomposition of CO_2 into CO due to elevated temperatures and moisture and metal catalysts in the cement kiln. Hydrocarbons are volatilized from the raw meal at the cold end of the kiln at temperatures below those necessary for complete destruction and oxidation. Additionally, although excess oxygen conditions (an oxidizing atmosphere) are required for quality cement production, low kiln levels (1 to 4% in cement kilns, compared with 5 to 10% in hazardous waste incinerators) are desired for high temperature, energy efficient operation. Low oxygen levels may lead to local oxygen-deficient regions and incomplete destruction of volatiles.

2.3 Lightweight Aggregate Kilns

“Lightweight aggregate” (LWA) is a high strength, lightweight material, with a density much less than ordinary aggregates such as gravel, sand, or stone. Its primary use is in concrete, made by combining LWA with cement. Lightweight aggregate concrete blocks and structural concrete are frequently used in the construction of roads, bridges, and buildings. There are over 36 LWA producing facilities in the United States. Of these, there are 3 which are burning hazardous waste derived fuel.

2.3.1 Process Components

A lightweight aggregate plant is composed of a quarry, a raw material preparation area, a kiln, a cooler, and a product storage area. The material flows from the quarry to the raw material preparation area. From there, the material is fed into the rotary kiln.

Lightweight aggregate is made by heating raw materials such as clay, shale, and slate to high temperature in a rotating lightweight aggregate kiln (LWAK), as shown in Figure 2-15. When the highly siliceous raw material is heated, it bloats and expands forming a strong light weight material when cooled. The kiln is a long steel cylinder (typically 120 to 300 feet in length with a 7 to 10 foot diameter), lined internally with refractory bricks. It rotates about its axis at 3 to 5 revolutions per minute, and is inclined at an angle of 3 to 5° from the horizontal. It operates in a manner similar to previously described for cement kilns. Crushed raw material is continuously fed to the kiln at the upper “cold” end. Gravity and kiln rotation cause the material to travel downward through the kiln toward its bottom end. At the bottom “hot” end, fuels such as coal, petroleum coke, natural gas, fuel oil, and/or hazardous waste are burned with air to provide energy to heat the raw materials. Combustion air is provided in an excess (80 to 100% of minimum requirements) to aid in “expanding” the raw materials. The raw material traveling down the kiln (from the upper to lower end) is heated by hot fuel combustion gases moving in an opposite direction (from the lower to upper end). This “counter-current” operation provides for efficient heat transfer between the hot gases and raw material, leading to a minimization of fuel energy requirements. Energy requirements are typically 3 to 6 million Btu/ton of LWA product.

The raw material goes through various temperature regimes as it is heated in the kiln which causes the transformation of the material into the LWA product. In the first preheating stage, raw material moisture is driven off. As the temperature increases, the material becomes soft and pliable and decomposes. Formation of internal gases (such as SO₂, SO₃, CO₂, and O₂) also begins. These gases cause the material to expand. When the material temperature approaches the “expanding” zone temperature of 1,900 to 2,100°F, it becomes sufficiently viscous to internally trap the expanding gases. This bloating action produces small unconnected gas cells, which the material retains after it cools and solidifies. These internal gas cells give the aggregate its characteristic light weight property. Maintaining the proper temperature is critical for making LWA. If the temperature is too low, the clay will not expand to form the desired structure. However, if the temperature is too high, the material fuses, leading to the formation of a heavy coating on the kiln interior that must be removed after shutting down and cooling the kiln. Kiln temperature is controlled by adjusting fuel and raw material feed rates, kiln rotation rate, and the amount of combustion air. The hot LWA product is removed at the bottom of the

kiln, and cooled. The LWA may be graded and crushed after cooling. Lightweight aggregate kiln production rates typically range from 200 to 1,000 tons of LWA/day.

An induced draft fan is used to pull combustion gases up through the kiln and to maintain a negative kiln pressure with respect to the atmosphere to prevent fugitive gas emissions from leaking through the rotary kiln seals. Kiln exhaust gases leave the cold upper end of the kiln at a temperature from 400 to 1,000°F. The kiln exhaust gas contains suspended dust particles (consisting potentially of raw material, waste ash, and fuel ash) and may also contain volatile inorganics such as acid gases (including HCl and SO₂ produced as a byproduct of the combustion of chlorine and sulfur containing wastes and fuels) and certain volatile metals. The LWAK exhaust gas may also contain elevated levels of unburned organics and CO compared with hazardous waste incinerators due to “counter-current” operation; at the upper kiln end, as the raw material is heated, organics may be vaporized at temperatures below those required for their complete oxidation and destruction.

Lightweight aggregate kilns historically have used both wet scrubbers and dry systems such as FFs and ESPs for exhaust gas dust emissions control. All hazardous waste burning LWAKs currently use FFs for the removal and collection of dust contained in the exhaust gas. The exhaust gas may require cooling (with either a water spray, heat exchanger, or cold air dilution) prior to the FF due to fabric operating temperature limitations. The collected dust can be recycled back into the kiln (at the hot or cold end) or mixed into the final LWA product. Some LWAKs also use dry scrubbing (by the addition of an acid gas absorbing alkali upstream of the FF) or wet scrubbing techniques for acid gas emissions control.

In currently operating hazardous waste burning LWAKs, only liquid hazardous wastes are treated. Liquid wastes are either blended directly with conventional fuels provided at the hot end of the kiln, or they are injected separately through a lance or atomizer into the hot end flame. The high combustion gas flame temperature (greater than 3,000°F) and kiln gas residence time (greater than 2 seconds) is used to destroy hazardous organics; waste inorganics are either incorporated into the LWA product or leave the kiln with the exhaust gas (in the form of either vapors or solids). Similar to cement kilns, LWAKs may potentially be used to treat solid wastes. Fine powder combustible solids may be injected similar to liquids directly into the hot end flame. Bulk solids may be introduced at mid-kiln through mid-kiln hatches or with air-cannon injection from the hot end.

2.3.2 Operating Parameters

Kiln operating parameters such as flame temperature, excess air level, feed size, material flow, gas and solids residence time, and speed of rotation vary from plant to plant and are determined by the characteristics of the raw material. Raw materials include clay, shale, or slate which have varying properties linked to their geological formation. As mentioned, maximum temperature in the rotary kiln varies from 2,050 to 2,300°F, depending on the type of raw material being processed and its moisture content. Kiln exit gas temperatures may range from 300 to 1,200°F, again depending on the raw material and on the kiln’s internal design. Approximately 80 to 100% excess air is forced into the kiln to aid in expanding the raw material.

A typical lightweight aggregate rotary kiln has a combustion gas residence time of greater than four seconds, based on a kiln gas temperature at the hot end of 2,100°F and a temperature at the cold end of 700°F.

2.4 Boilers

Under the Resource Conservation and Recovery Act, 40 CFR 260.10, a boiler is defined as an enclosed device using controlled flame combustion with the following characteristics:

- The combustion chamber and energy recovery section must be of integral design.
- Thermal recovery efficiency must be greater than 60%, determined as the ratio of the recovered energy to the thermal value of the fuel.
- Greater than 75% of the recovered energy must be exported and used (i.e., this does not include internal boiler uses such as preheating combustion air or driving combustion air fan or feedrate pumps).

Boilers burning hazardous waste can be categorized by fuel type and boiler heat transfer design:

- Liquid fuel boilers: There are about 85 unique boiler units which fire liquid hazardous wastes and liquid/gas auxiliary fuels such as natural gas, fuel oil, or process gas:
 - Watertube units burning liquid/gas fuels -- Forty units, ranging in size from 20 to over 500 MMBtu/hr. Most do not use any air pollution control equipment downstream of the boiler. A couple do: 1 uses a FF; 2 use ESPs; and 1 uses a VS.
 - Firetube units burning liquid/gas fuels -- About 10 units, ranging in size from 20 to 60 MMBtu/hr. Six of these units use a series of wet scrubbers for the control of HCl due to the burning of high chlorine content wastes. One unit, which burns mixed hazardous and radioactive contaminated wastes, uses a series of wet scrubbing, and filtering with a FF and HEPA.
 - Process heaters -- About 10 units, burning liquid wastes, are process heaters, which heat process fluids such as oil or Dowtherm, as opposed to water.
 - Unknown design burning liquid/gas fuels -- Twenty five units are of unknown boiler design. Most do not use air pollution control equipment downstream of the boiler.
- Solid fuel boilers: There are 8 units which burn liquid hazardous wastes and coal:
 - Watertube units burning solid/liquid fuels -- Eight units burn coal and liquid waste fuels. Two of these units also burn non-hazardous sludges. Two of the

sources use FFs; the rest use ESPs. Both pulverized coal and stoker firing setups are used.

Almost all boilers are captive units which burn waste generated on-site. A couple accept wastes from off-site.

2.4.1 Heat Transfer Configuration

Boilers can be sub-classified into three different types based on their heat transfer configuration set-up: (a) watertube; (b) firetube; and (c) cast iron. The choice of design depends on factors including the desired steam quality, thermal efficiency, size, economics, fuel type, and responsiveness.

Watertube

Hazardous wastes are commonly burned in industrial watertube designed boilers. This is due to watertube boiler ability to: (a) produce high quality steam at high pressure (up to 1,750 psi) and high temperature (1,000°F); (b) achieve high thermal efficiency; (c) respond rapidly to changes in steam demand; and (d) potentially burn a variety of fuel types including coal, oil, gas, and other fuel types such as wood and municipal wastes. Watertube boilers burning hazardous wastes have a wide range of sizes, from smaller package units at 15 to 100 million Btu/hr, to over 1,500 million Btu/hr for larger field erected utility-type units.

A typical industrial watertube boiler is shown in Figure 2-16. A watertube boiler contains furnace and convective sections. In the lower furnace section, the fuel is burned. As discussed in the next section, depending on the burner and fuel feed design set-up, gas, liquid, and solid fuels (including hazardous wastes) can be burned. The furnace section is lined with small diameter tubes which carry flowing water. Radiative heat from the fuel combustion flame heats the water in the tubes, creating steam.

The combustion flue gases are routed from the furnace into the “convective” section of the boiler. This section typically contains a superheater, reheater, economizer, and air preheater heat exchangers. The superheaters and reheaters are designed to increase the temperature of the steam generated in the furnace section. Following the superheater and reheater, an economizer counterflow tube heat exchanger is used to initially heat the boiler water before entering the furnace tube wall. The air heater is used to preheat the furnace combustion air. These separate operations all increase the boiler thermal operating efficiency.

Steam tubes are both imbedded in the furnace wall and mounted in the convective heat exchanger bundles which are exposed to the hot flue gases (such as in the superheater and reheater). The steam tubes are connected to one or more “steam drums” which collect the generated steam. Residues that collect and concentrate in the water/steam are collected at the “mud drum” located at the bottom of the tubes.

Soot, ash, and other solid deposits that are generated from waste and/or other fuel combustion (such as natural gas, fuel oil, process gas, etc.) tend to deposit and buildup on the boiler tube surfaces. “Sootblowers” are used periodically to clean the tubes of this particle buildup.

Firetube

Hazardous wastes are also commonly burned in firetube boilers. Firetube design boilers are used for applications where smaller steam production and lower steam quality is required, and steam load requirements are relatively constant. Most units are less than 20 MM Btu/hr in size. Firetube boilers are compact, modular, and have low initial capital and installation cost. Packaged units usually have the capability of firing gas and liquids. Solid fuel firing in firetube boilers is rare due to clogging of tubes with ash and slag residue. Disadvantages to the use of firetube boilers include: (a) inability to superheat steam; (b) limit on steam pressure of 150 to 250 psi; (c) slow response to changes due to larger thermal inertia; and (d) lower thermal efficiency compared with watertube units.

Firetube boiler design is similar to a shell-and-tube heat exchanger. Shown generally in Figure 2-17, firetube boilers consist of a water-filled cylinder with immersed tubes passing through it, usually making multiple passes back and forth through the cylinder. Combustion gases are routed through the inside of the tubes and transfer heat to the pool of water to produce steam. Depending on the tube and firing arrangement, firetube boilers are generally classified as:

- Horizontal return tube -- Externally fired arrangement, where fuel combustion occurs in a separate refractory lined furnace area.
- Scotch marine (or shell) -- Internally fired firetube boiler, where the boiler and furnace are contained in the same shell. Fuel is combusted in a flue furnace, which is composed of a large tube or pipe oriented horizontally in the water basin. The flame is designed to extend across most of the flue length. Combustion gases then make multiple passes through the water in smaller firetube sections.
- Firebox -- Similar to the horizontal return design, except that the furnace walls are also surrounded by the boiler water.

Cast Iron

Cast iron boilers are the smallest of the three boiler types, with a maximum size of 10 million Btu/hr. They are generally used for producing low quality steam or hot water for commercial or institutional boiler applications. Pressure limits range from 15 to 100 psi for hot water and steam units. They are not used for burning hazardous wastes.

2.4.2 Fuel / Waste Type

All hazardous wastes currently being burned in industrial boilers are in the form of pumpable liquids, sludges, or slurries. There are no solid hazardous wastes being burned in industrial boilers. Most hazardous waste burning boilers are co-fired with natural gas, fuel oil, or process gases. This is to ensure proper combustion temperatures are achieved, and/or that a consistent supply of steam is produced. Boilers can be classified as either liquid or solid fuel burning systems, depending on the auxiliary, non-hazardous waste fuel, that is used:

- Liquid fuel boilers – The majority of boilers are limited to burning liquid or gas fuels and wastes. This includes all firetube units, and most waterwall units. These boilers are not physically configured to fire solid wastes – the burner and feed system design do not allow the use of non-liquid wastes, and the boiler is not designed to remove ash generated from solid waste combustion. Major boiler modifications (to burners, ash removal systems, combustion air distribution systems, etc.) would be required to allow the firing of non-pumpable, solid bulk wastes.
- Solid fuel boilers – There are a few liquid hazardous waste burning waterwall boilers that are co-fired with coal. These units include both suspension (pulverized coal) firing and stoker units, as discussed below.

It is possible that these boilers could in the future burn certain forms of solid hazardous wastes. Pulverized coal boilers could potentially burn homogeneous, size reduced, solid hazardous waste forms; stoker boilers could burn wastes with more heterogeneity and larger particle sizes compared with pulverized boilers (but still much more limited in waste form and composition than, for example, rotary kiln incinerators).

Most pulverized coal boilers use multi-fuel burners which are designed to burn either natural gas, fuel oil, or pulverized coal. All hazardous waste burning pulverized coal boilers are currently setup to burn combinations of coal, natural gas, process gas, and/or liquid hazardous wastes.

Most stoker coal boilers are also configured to burn natural and/or process gases. Most often, coal chunks are transported/mixed with supplemental gas or oil to help the fuel burn in the stoker bed. However, this is not always the case – there are stoker boilers which do not have sufficient natural gas pipe lines for running the boiler on natural gas.

Liquid Waste Combustion Burners

Liquid waste combustion is done in a manner identical to that for conventional fuel oil combustion or liquid injection incineration. In a liquid/gas burner, atomized liquid wastes/fuels are mixed with combustion air in a swirling manner to provide a stable flame. Liquids can be fed and atomized in the main burner, or injected into the main flame through auxiliary lances. Liquid atomization is achieved through mechanical methods such as rotary cup or pressure atomization systems, or by twin-fluid nozzles with the assistance of high-pressure air or steam. With a high surface area, the atomized particles vaporize quickly, forming a combustible mixture of fumes and combustion air that rapidly ignite and burn.

Liquid wastes with high solids need to be filtered prior to feeding. Additionally, wastes with viscosities of greater than 10,000 SSU may require pretreatment (heating to decrease viscosity or blending with lower viscosity liquids) prior to combustion.

In firetube boiler sets, a single burner is usually used. Watertube boiler setups use wall or tangential fired suspension systems, as discussed below.

Suspension Firing -- Gas, Oil, and Pulverized Solids

Suspension firing set-ups are used in watertube boilers for gas (most commonly natural gas, also process gases), liquid (e.g., fuel oil, hazardous liquid wastes), and pulverized solids (e.g., pulverized coal). Suspension firing arrangements in watertube boilers include:

- Wall (face) fired -- Horizontally mounted burners in either a single (front) wall or opposed wall set-up.
 - Front wall fired -- Usually use a single burner, although there are some older and larger units which may use multiple burner rows. Newer units use single burners which can provide required control and turndown.
 - Opposed wall -- Used mostly in larger utility applications.
- Tangential (corner) fired -- Horizontally mounted burners in the four corners of a rectangular furnace, all firing toward the center to produce a cyclonic fireball.
- Cyclone -- Fuel (usually pulverized coal) and air is fed circumferentially into a cylindrical combustion chamber. Not widely used for industrial purposes (mostly for larger utility applications).

Pulverized coal units can be either a wet bottom or dry bottom design, depending on if the ash is handled as a dry solid (dry bottom) or a molten liquid slag tap (wet bottom). Pulverized coal units are usually large (greater than 100 million Btu/hr) due to the high cost of the coal pulverizing and handling equipment.

Stoker Firing -- Solids

Stoker fired boilers are designed to burn solid fuels (including coal, wood, municipal wastes, etc.) in a bed. Stoker systems are used on many coal-burning (and other solid fuel) industrial, commercial, and institutional boiler applications. This is because fuel handling and pretreatment procedures are not typically required.

Stokers are mechanical or pneumatic devices that feed solid fuels onto a grate at the bottom of the furnace and remove the ash residue after combustion. They consist of: (a) a fuel supply system; (b) stationary or moving grate which supports the burning mass of fuel and admits most of the combustion air to the fuel; (c) an overfire air system, provided over the burning bed,

to complete combustion; and (d) an ash or residual discharge system. In most stokers, fly ash collected downstream of the furnace is reintroduced into the bed to ensure complete combustion of the fuel.

There are three main classes of stoker set-ups: (a) underfeed, (b) overfeed, and (c) spreader stoker:

Underfeed -- In underfeed stokers, the solid fuel is fed to the bottom of the fuel bed. Moisture and volatiles are driven off initially from the fuel in the bed; the volatiles undergo combustion above the bed. Fuel ash is passed out the sides of the grate as fresh fuel is added. Combustion air enters through sides grates. There are two primary types of underfeed stoker designs: (a) horizontal feed, side ash discharge; and (b) gravity feed, rear ash discharge.

Overfeed -- Fuel is fed onto a moving grate that travels through the furnace chamber. There are three types of grate designs: (a) chain-grate, (b) traveling-grate, and (c) water-cooled vibrating grate. Combustion air is fed up through the bottom of the grate. Overfire air is also usually used to complete combustion.

Spreader Stoker -- Spreader stokers are a type of overfeed design where fuel is evenly spread over the fuel bed with mechanical or pneumatic assistance, as shown in Figure 2-18. Various different types of grates can be used, including: (a) stationary and dumping grate; (b) vibrating grate; (c) traveling grate; and (d) vibrating water cooled grate. Combustion air is provided both under and over the grate.

Fluidized Beds

Fluidized bed systems can be used to efficiently combust various types of solid and liquid fuels. Size reduced fuel (ground or shredded) is fed into a bed of inert particles (sand and/or a sorbent such as limestone). The bed is kept suspended (“fluidized”) by an upward flow of combustion air through the bed. There are currently no fluidized bed type industrial boilers which burn hazardous waste.

2.3.3 Operating Conditions

Flame combustion temperatures in industrial boilers typically range from 1,800 to 2,200°F, depending on waste and fuel heating value and composition and oxygen supply. Air is supplied in excess to ensure adequate combustion conditions and complete burnout of fuel organics, typically at an excess oxygen level of 3 to 6% by volume in the flue gas. However, it is also desired to minimize the oxygen supply to increase boiler operating thermal efficiency and maintain combustion temperature. Auxiliary fuels (natural gas, fuel oil, coal, process gas) are provided as necessary to assist in maintaining adequate combustion temperature, combustion quality, and steam production rates. Stack gas CO and O₂ CEMS are used to effectively control the fuel and oxygen supply rates.

Combustion gas cooling occurs primarily by radiative transfer from the flame to the water-steam tubes imbedded in the furnace walls, and continues by convective heat transfer in the downstream convective tube heat-exchanger tubes passes. Combustion gas cooling occurs at a rate of about 150 to 350°C per second of combustion gas residence time.

2.3.4 Air Pollution Control Methods

Liquid / Gas Units

Most boilers that are limited to firing hazardous waste liquids and gas or liquid auxiliary co-firing fuels do not use air pollution control devices for PM, metals, or acid gas control. Current RCRA BIF standards, including those for PM, metals, and chlorine, are met solely through control of hazardous waste (and all other feedstocks) feedrate characteristics including ash, metals, and chlorine content. Thus, most of the metals and chlorine BIF feedrate limits are met through Tier I procedures, where it is conservatively assumed that no system control is being achieved (what is fed is assumed to be emitted out the stack).

A few units which burn liquid wastes (or liquid auxiliary fuels such as low-grade residual fuel oils) use PM, metal, and/or acid gas control devices, including wet scrubbers, ESP, or baghouses. In particular, a number of boilers burning highly chlorinated liquid and/or solid wastes use wet scrubbers for the control of acid gas emissions.

Organic emissions are controlled through continuous emissions monitoring of CO (or HC) as required under the current BIF rule. CO and HC emissions are controlled through maintaining efficient combustion conditions, including providing adequate combustion air, air/fuel mixing, minimum combustion temperature, etc. PCDD/PCDF emissions are controlled through limiting dry PM air pollution control device temperature.

Solid Units

All solid fuel (coal-fired) fired boilers use some type of PM control, most commonly with ESPs, and less frequently, baghouses. This is primarily to control the fly ash produced from the combustion of coal. No air pollution control devices are used for the control of acid gases such as HCl or SO₂. Organic emissions are controlled through maintaining good combustion conditions and practices, similar to those for liquid boilers.

2.5 Process Heaters

Process heaters are used to burn liquid hazardous wastes at a couple of facilities in the chemical and petrochemical industries. Process heaters are very similar in design and operation to the above described liquid fuel fired boilers. The primary difference is in the type of fluid which is used for heat transfer. As opposed to heating water to steam as is done in boilers, process heaters use a different fluid, typically oil or some other high efficiency heat transfer fluid (such as Dowtherm). Process heaters are used when heat must be transferred at low pressure at temperatures in excess of 200 to 400°F.

Some process heaters are similar in design to small watertube boilers. Fuel is burned in a combustion chamber, whose walls are lined with tubes contained the process fluid which is heated through flame radiation. A convective section of process fluid tube banks is usually used to transfer additional heat from the combustion gases to the process fluid. Other process heaters are more similar to firetube boilers, where hot fuel combustion gas products are routed through a process fluid heat exchanger.

Fuels include natural gas, process gas, fuel oil, and liquid hazardous wastes. Solid fuels are not used in hazardous waste burning process heaters.

Typically, due to the limited use of clean burning fuels, process heaters do not use PM or acid gas air pollution control devices. Organic emissions are controlled through the use of good combustion practices, identical to boilers discussed above.

Process heaters are grouped (combined) with liquid fuel boilers for the purpose of setting (and complying with) MACT floor emissions levels. This is due to their very similar design and operation, similar fuel types, similar emissions characteristics, and because emissions from each can be controlled using similar control devices or techniques.

All process heaters burning hazardous waste are “indirect” units, where the fuel combustion gases do not mix with the material being heated (hot oil, process gases, or Dowtherm fluid), and thus the gas emissions are related directly to the products of the fuel combustion. There is another class of process heaters which is referred to as “direct” process heaters, where the fuel combustion products are directly contacted with the heated materials, for example those used for metal heating operations.

2.6 Halogen Acid Furnaces

Halogen acid furnaces (HAFs) are units which meet the following requirements:

- They are located at the site of a manufacturing process.
- They burn hazardous wastes with a minimum as generated halogen content of 20% by weight to produce an acid product with a minimum halogen content of 3% by weight.
- They use the acid product in the manufacturing process.

Also, some HAFs burn halogen containing wastes partially for energy recovery in boilers because usable heat energy is released by the wastes during combustion.

There are over 15 different sources, operated by 6 different companies at 7 different sites. Most recover hydrogen chloride; a couple (at the Dow Freeport facility) recover magnesium chloride. A number of units use waste heat recovery boiler units prior to acid recovery in a series of absorbers and wet scrubbers. All burn hazardous liquid wastes.

HAFs are combustion units (many are modified firetube boilers) which use high temperatures to (in principle) process chlorinated, fluorinated, or brominated secondary liquid materials with high halogen content. Specifically, to produce and recover an acid product -- potentially either hydrogen chloride (HCl), hydrogen fluoride (HF), or hydrogen bromide (HBr). Hazardous wastes can be used to contribute halogen content, as well as to contribute heat energy for the combustion temperatures needed to convert halogen containing materials into acids which may be recovered.

A HAF is shown schematically in Figure 2-19. In the furnace section, acid-containing feedstreams, wastes, and auxiliary fuels (usually natural gas) are burned in a refractory lined chamber similar to a liquid waste incinerator chamber. The combustion is maintained at high temperature and with adequate excess hydrogen to ensure the conversion of halogens in the feedstreams to hydrogen halides (HCl, HBr, HF) in the combustion gases.

The furnace is sometimes directly attached to a firetube type boiler where waste heat from the combustion gases is recovered and the combustion gases are cooled. In other cases, a water spray quench is used to cool the combustion gases.

Cooled combustion flue gases are then routed to an acid recovery system, consisting of multiple wet scrubbing absorption units. These units are usually packed tower or film tray scrubbers which operate with an acidic scrubbing solution to remove the acid gas. The scrubbing solution is recirculated and concentrated until it obtains a desired acid concentration. The scrubber solution, containing the concentrated acid, is then removed and recovered as a valuable product.

A final polishing scrubber, operated with a caustic liquid solution, is used to complete the removal of remaining acids and free halogen gases (such as Cl_2 or F_2) prior to release of the flue gas to the atmosphere.

The scrubber sections also act to remove secondary combustion byproducts such as combustion ash and other solid inorganic constituents which are entrained in the combustion flue gas.

Organic emissions are controlled in a similar manner to liquid and solid fuel boilers -- through maintaining good combustion conditions.

2.7 Sulfuric Acid Recovery Furnaces

Sulfuric acid recovery furnaces that are burning hazardous waste are run by two companies:

- Rhodia (formerly Rhone Poulenc, Inc.) operates three SARF units which burn hazardous wastes: Hammond, Indiana; Houston, Texas; and Baton Rouge, Louisiana. The Hammond unit operates with a BIF interim status permit. The Houston and Baton Rouge

facilities currently operate with Subpart O incinerator permits; both are in the process of permitting as SARFs under BIF.

- Arch Chemicals (formerly Olin) in Beaumont, Texas.

Sulfuric acid recovery furnaces (SARFs) are used to recover sulfuric acid from used (spent) sulfuric acid and other sulfur bearing wastes. Most of the recycled spent sulfuric acid is generated at refineries from operations that produce gasoline.

A process diagram is shown in Figure 2-20. The acid recovery furnace is typically a horizontal, cylindrical, refractory-lined chamber, similar to a HAF or liquid waste incinerator. The sulfur containing wastes are burned, along with other combustible hazardous wastes and auxiliary fuel (natural gas), in the furnace. The spent acid is commonly contaminated with water, organics, inorganics and other materials from process use. Waste sulfur is thermally decomposed in the furnace to SO_2 in the combustion gas. Furnace combustion temperatures are maintained from 1,800 to 2,000°F

Combustion gases are initially cooled in an attached firetube waste heat boiler to about 700°F and then passed through a quench tower, packed tower gas cooler, wet ESP, and drying tower to remove particles, sulfuric acid mist, and HCl. The dry gas then passes through a series of heat exchangers to maintain an appropriate gas temperature, and then to a catalytic converter bed. The converter, made of vanadium pentoxide, facilitates the reaction of SO_2 and O_2 to produce SO_3 . The gas then is passed to absorbing towers where circulating sulfuric acid solution absorbs SO_3 to form commercial grade sulfuric acid ($\text{SO}_3 + \text{H}_2\text{O} = \text{sulfuric acid}$). This is followed by a mist eliminator and exhaust gas release.

Major emissions are SO_2 and sulfuric acid mist. Acid mist created when SO_3 combines with water vapor at a temperature below the dew point of SO_3 .

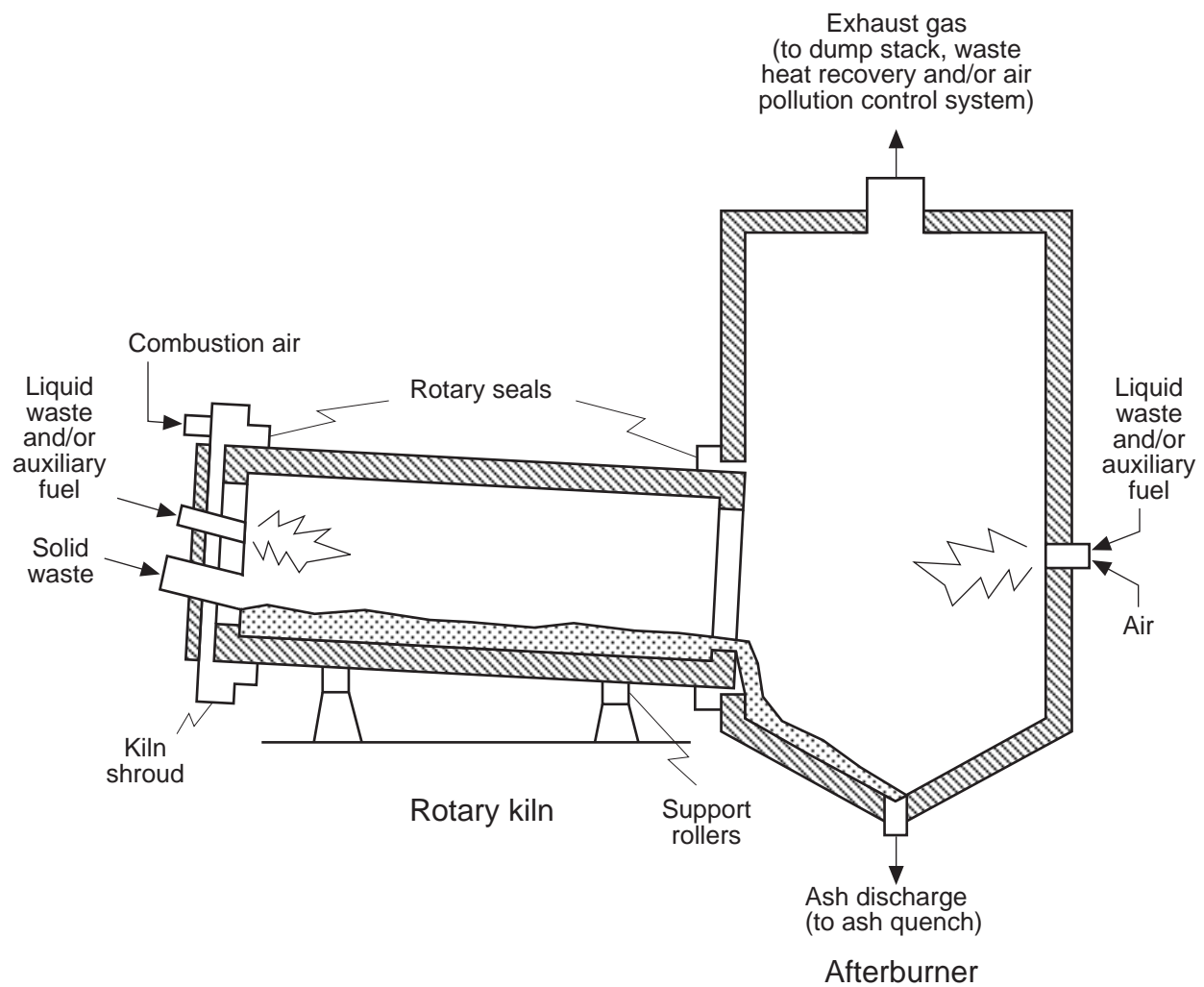


Figure 2-1. Typical rotary kiln incinerator.

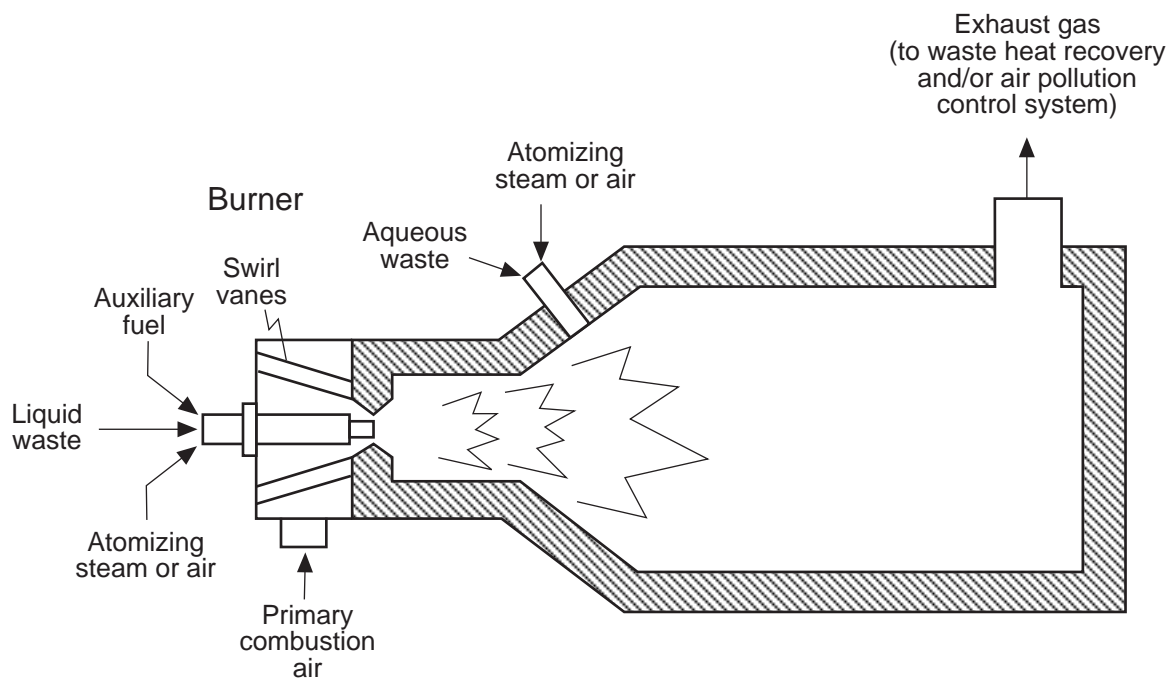


Figure 2-2. Typical liquid injection incinerator.

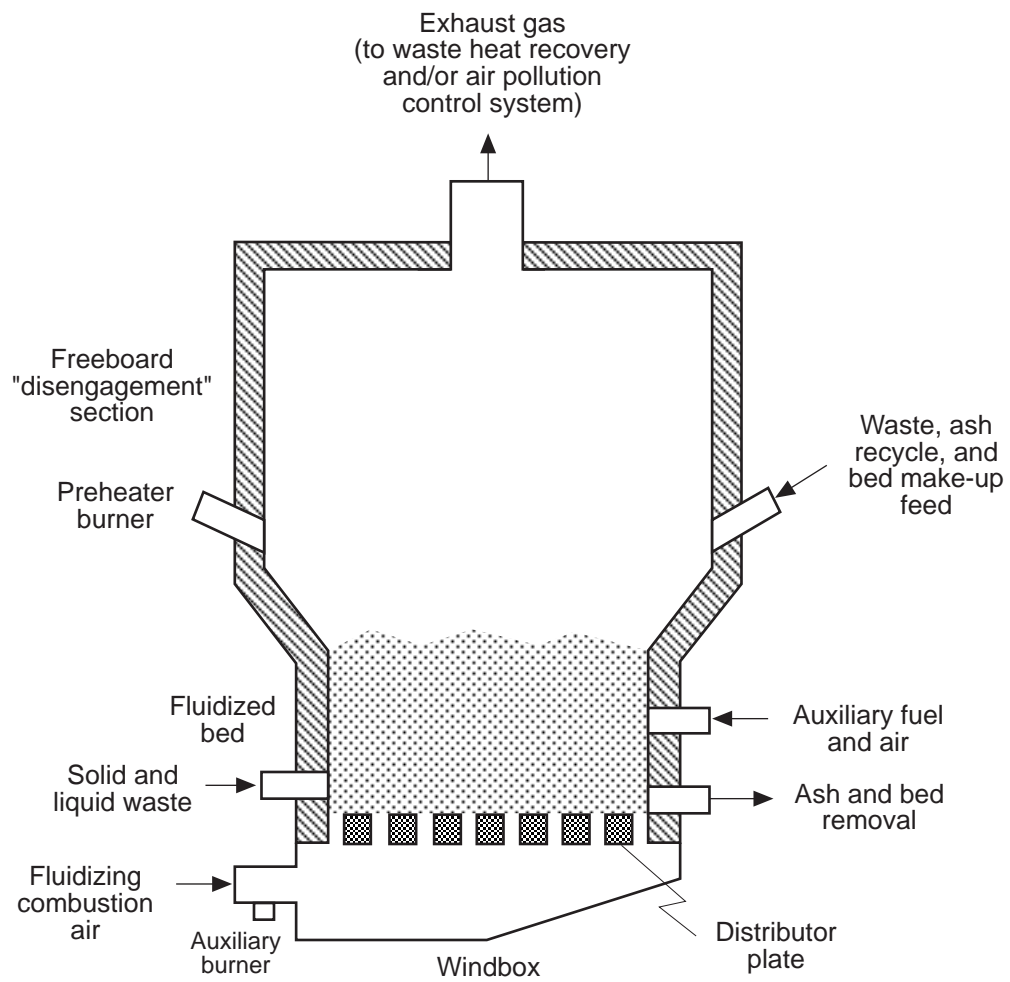


Figure 2-3. Typical fluidized bed incinerator.

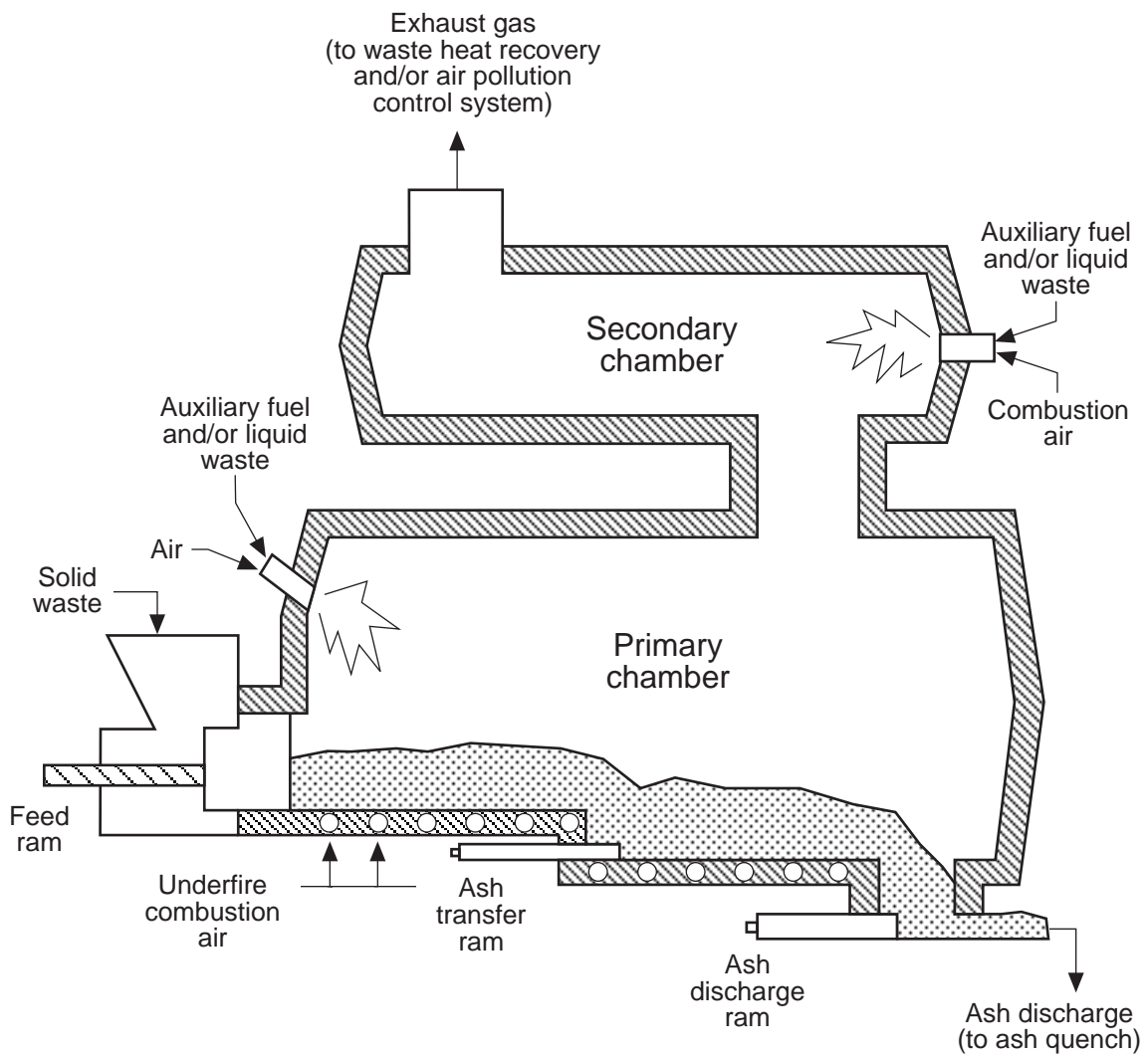


Figure 2-4. Typical fixed hearth incinerator.

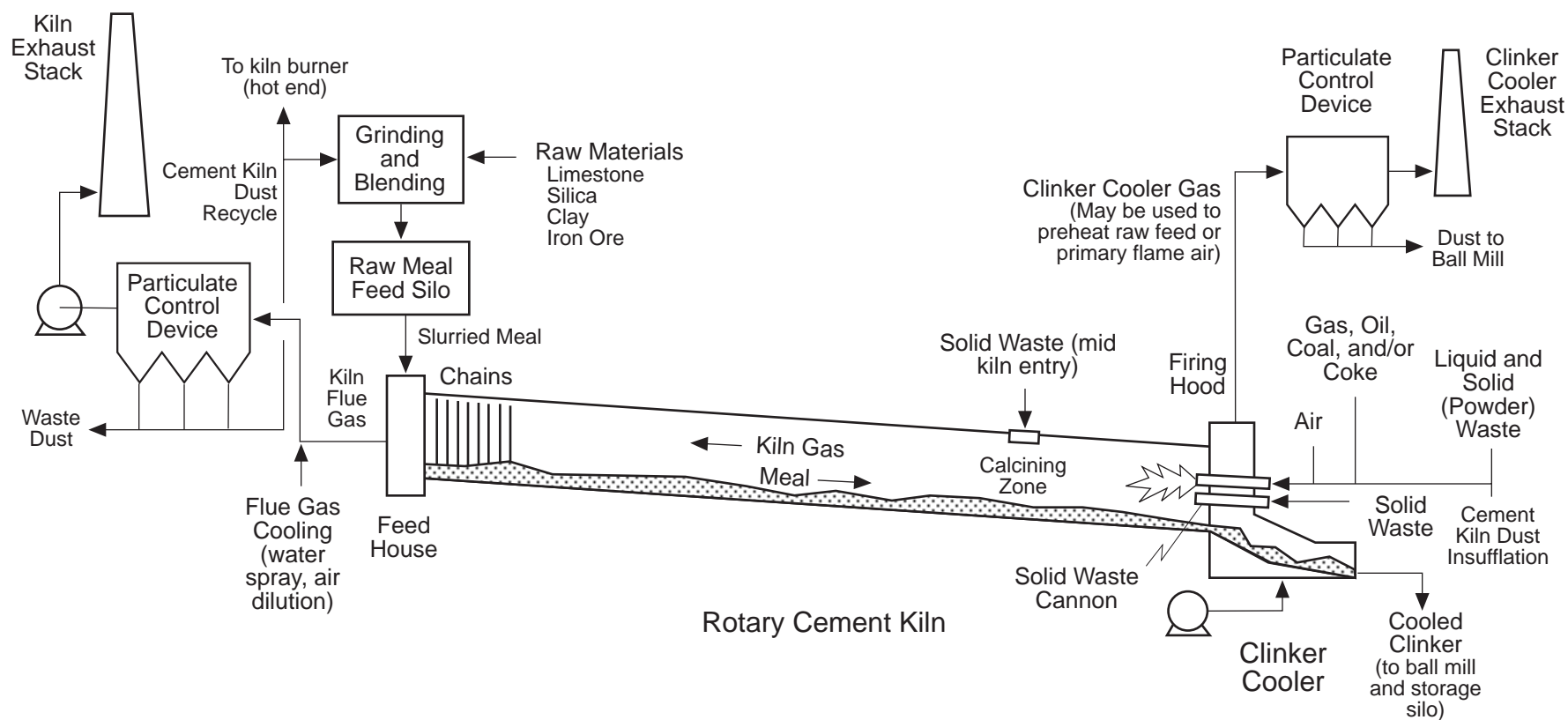


Figure 2-5. Wet cement kiln.

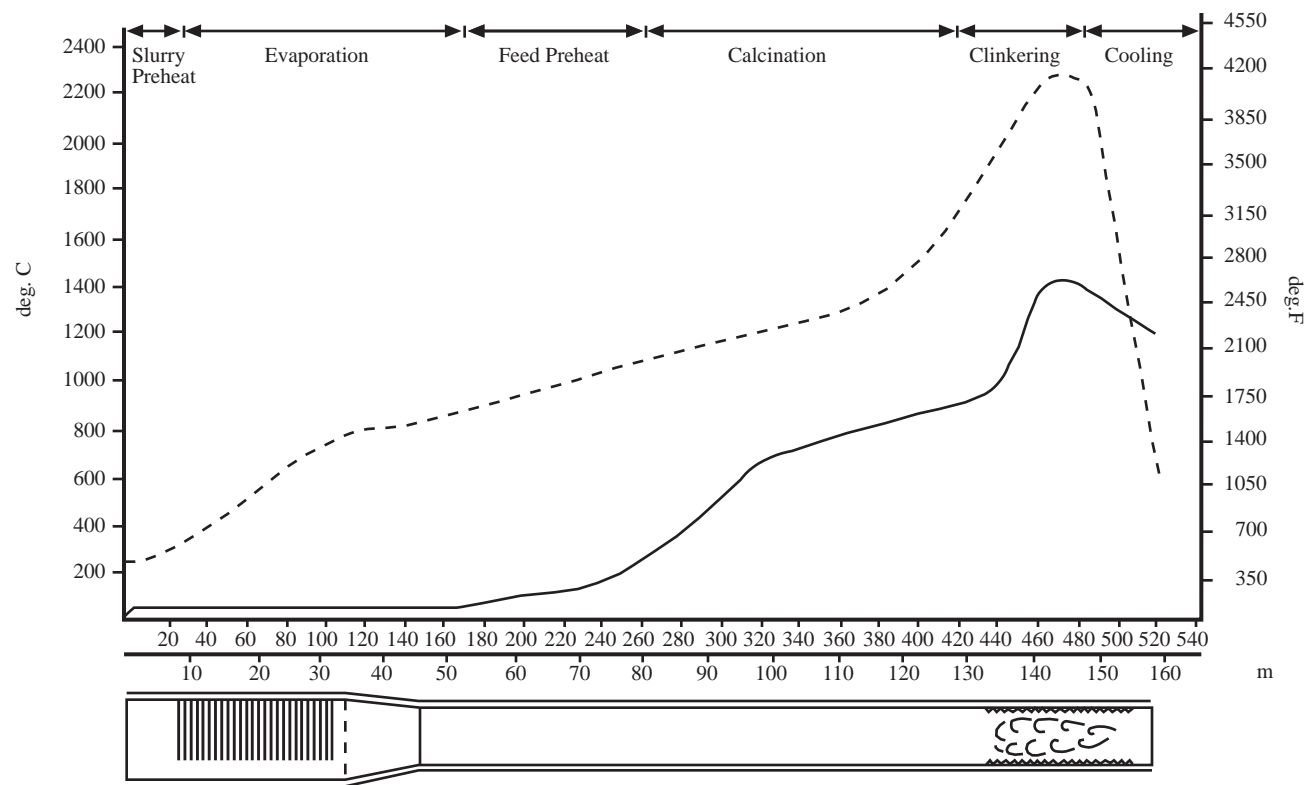


Figure 2-6. Typical gas (dashed line) and solids (solid line) temperature profiles for a long wet-process cement kiln.

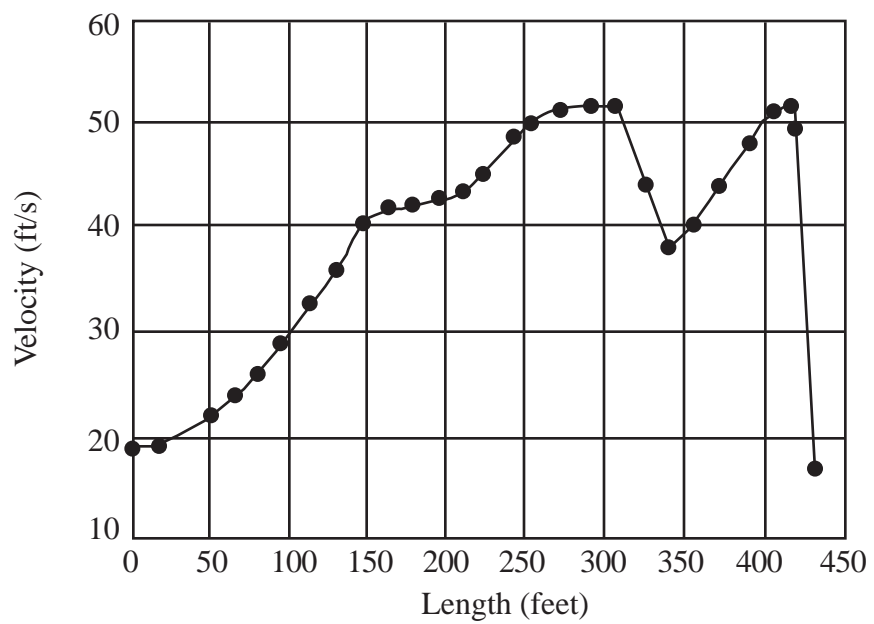


Figure 2-7. Typical gas velocities for a long wet-process cement kiln.

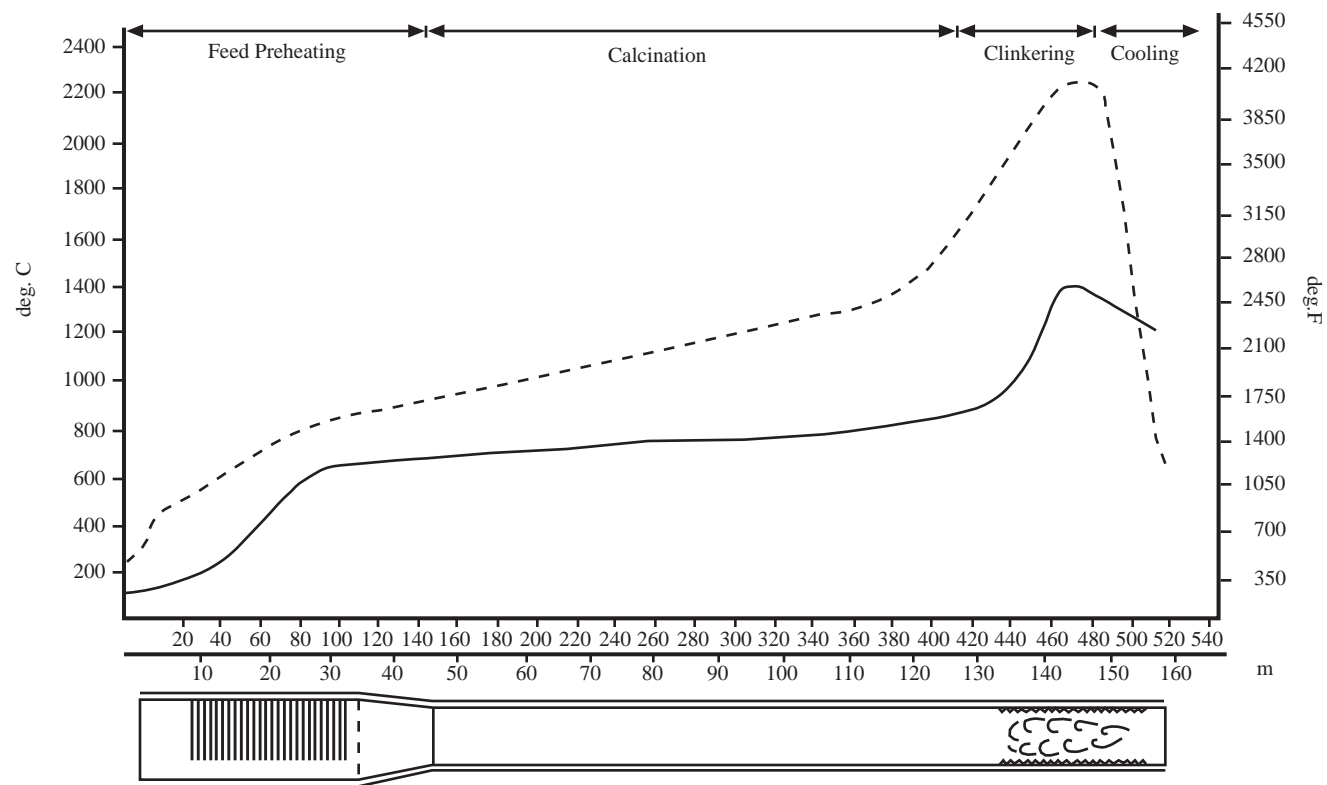


Figure 2-8. Dry kiln process material (solid line) and gas temperatures (dashed line).

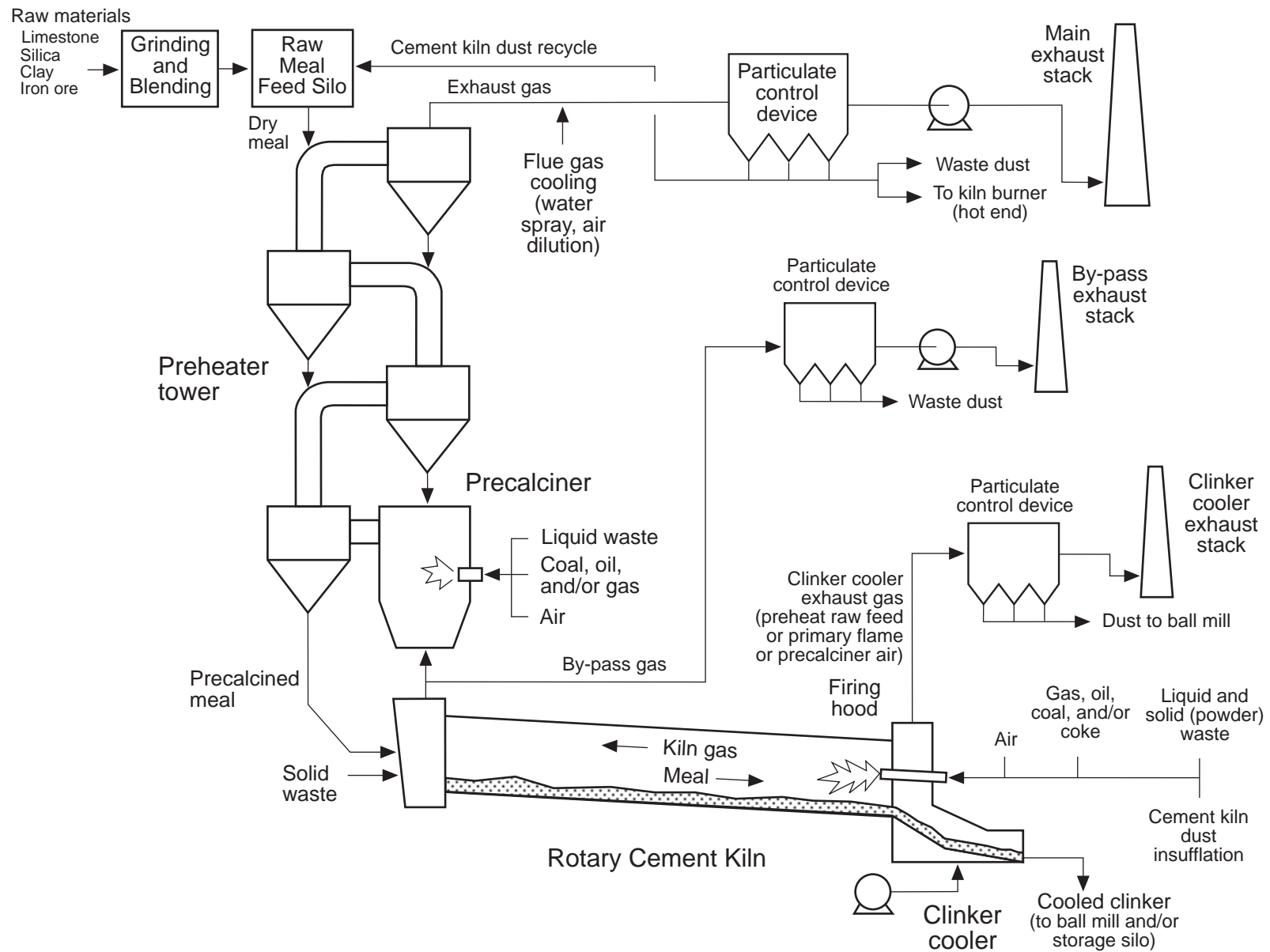


Figure 2-9. Dry preheater/precalciner cement kiln schematic.

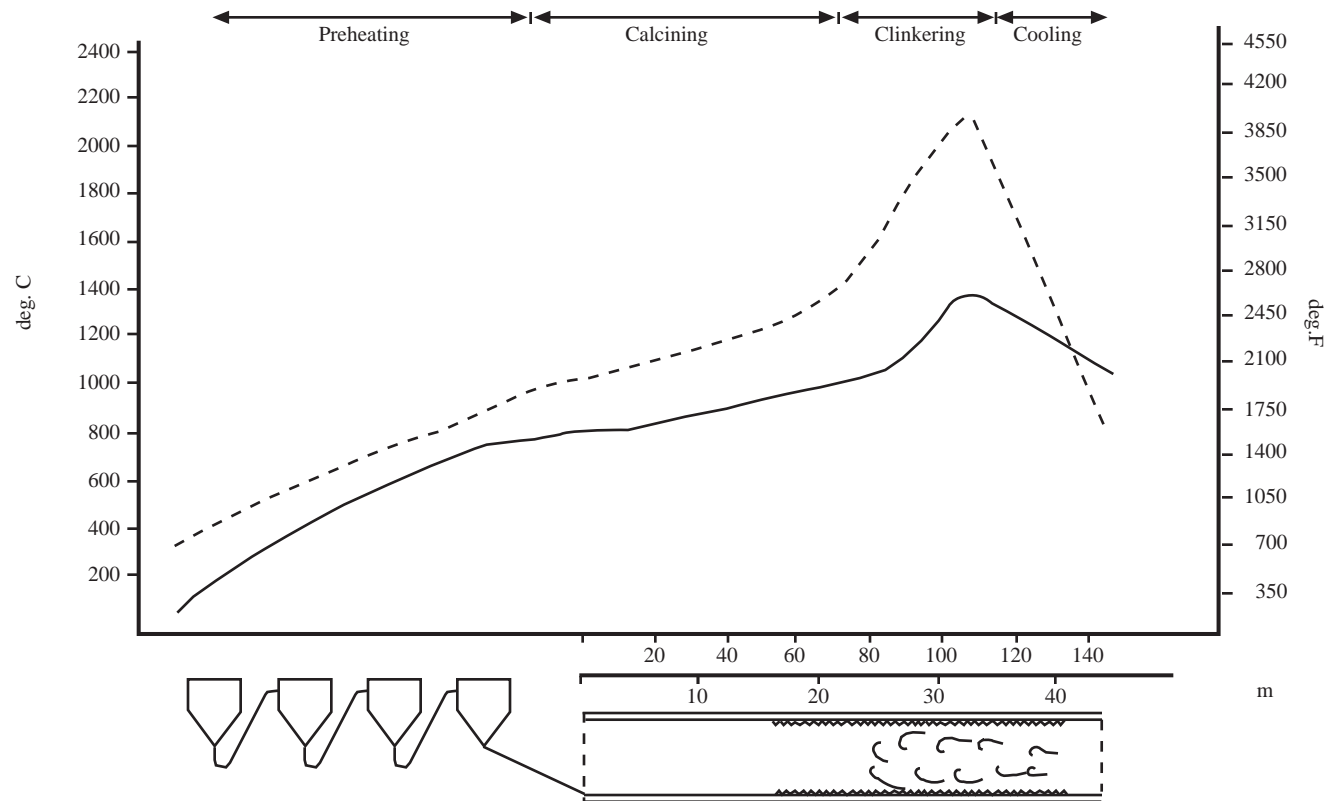


Figure 2-10. Typical gas (dashed line) and solids (solid line) temperature for a preheater cement kiln.

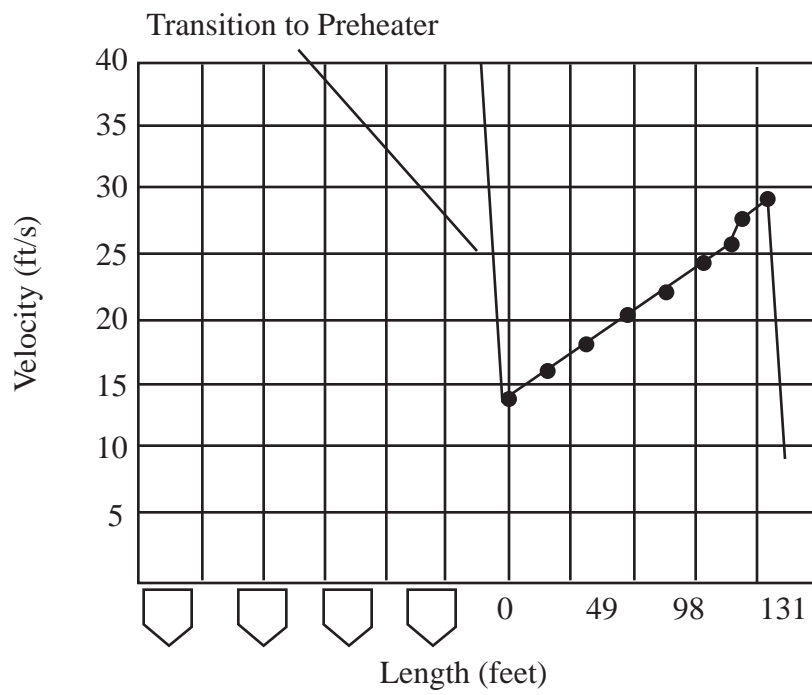


Figure 2-11. Typical gas velocities through a preheater cement kiln.

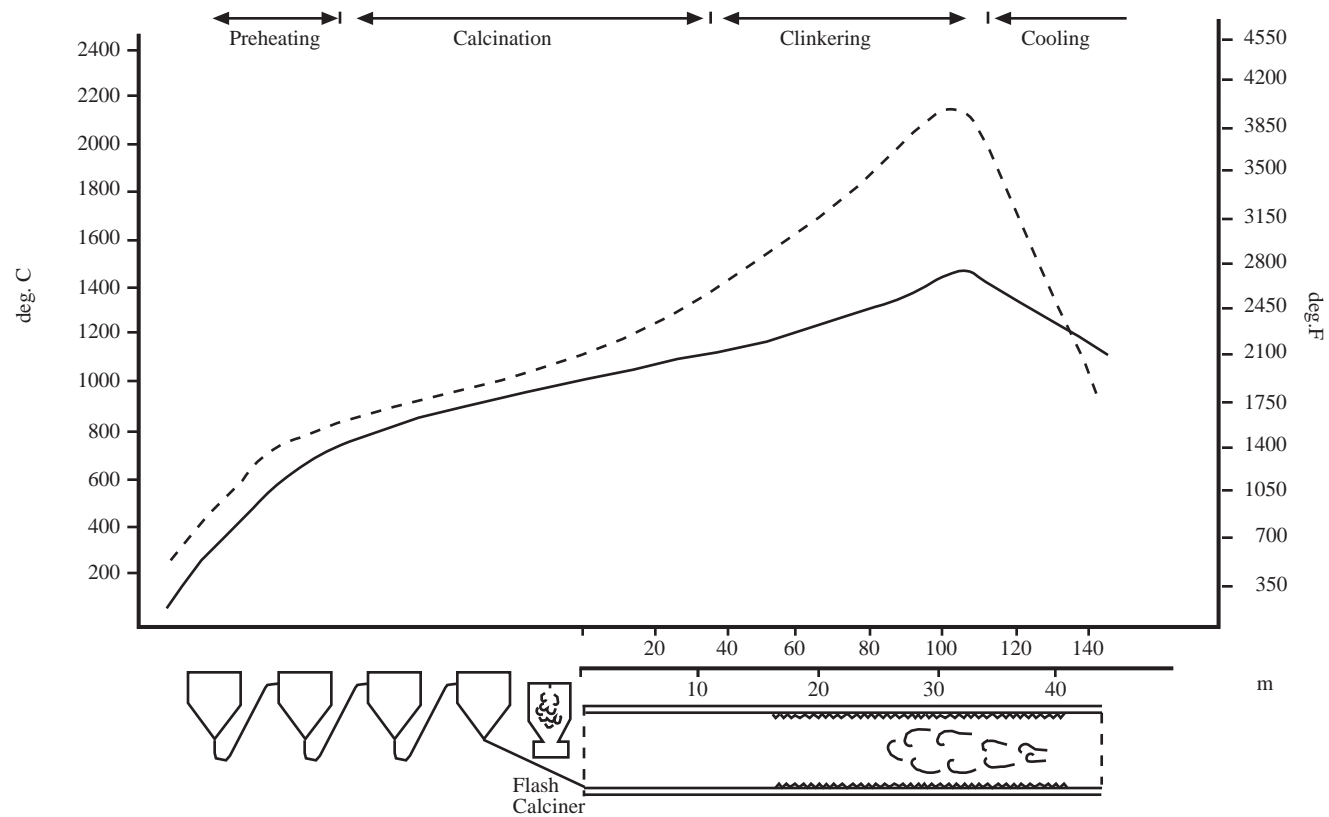


Figure 2-12. Typical gas (dashed line) and solids (solid line) temperature for a preheater/precalciner cement kiln.

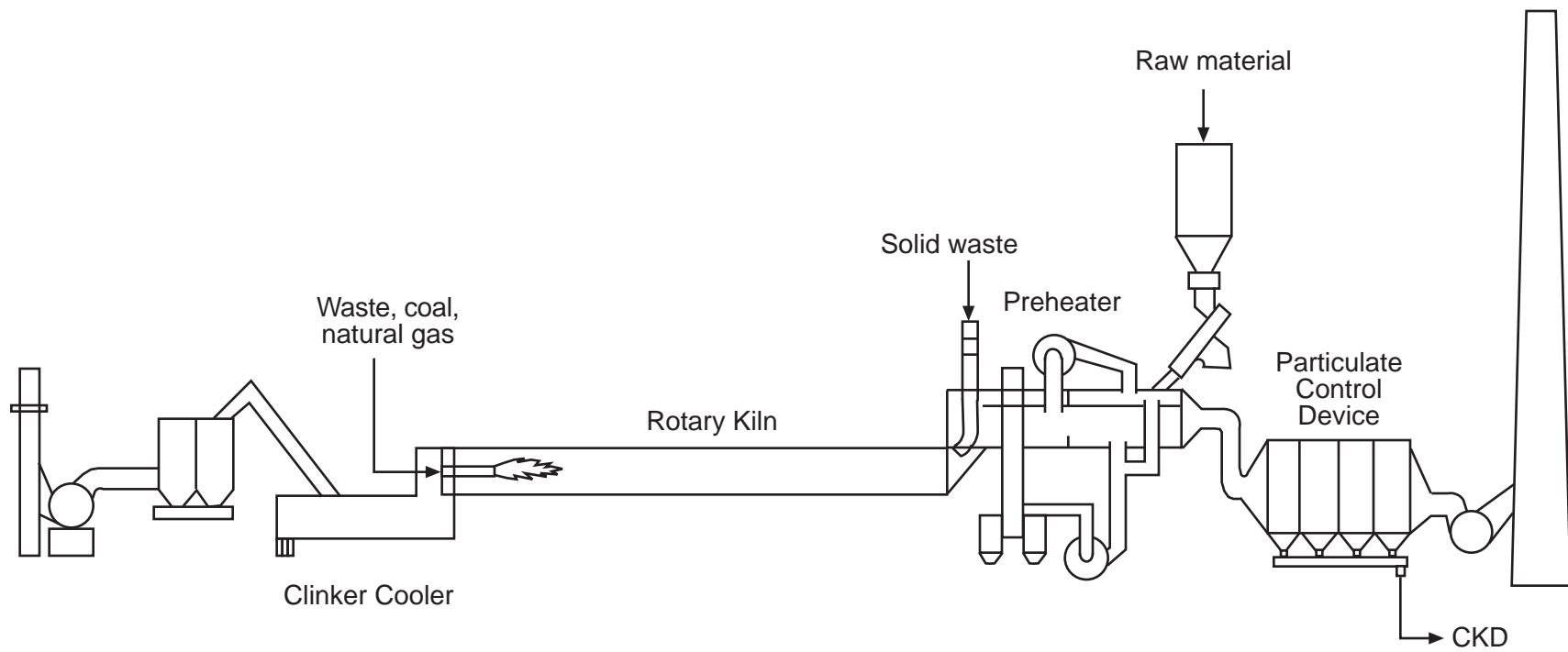


Figure 2-13. Semi-dry cement kiln.

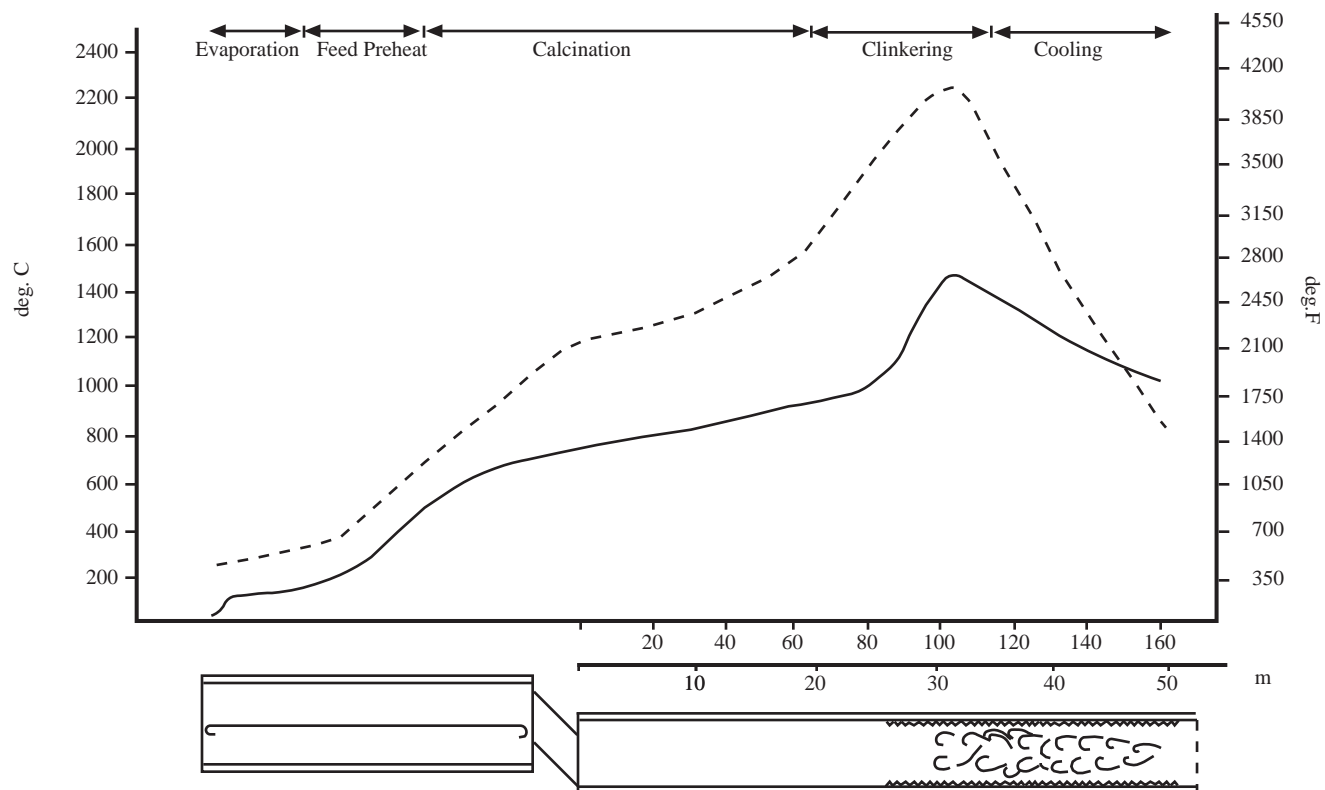


Figure 2-14. Semidry kiln material (solid line) and gas (dashed line) temperatures.

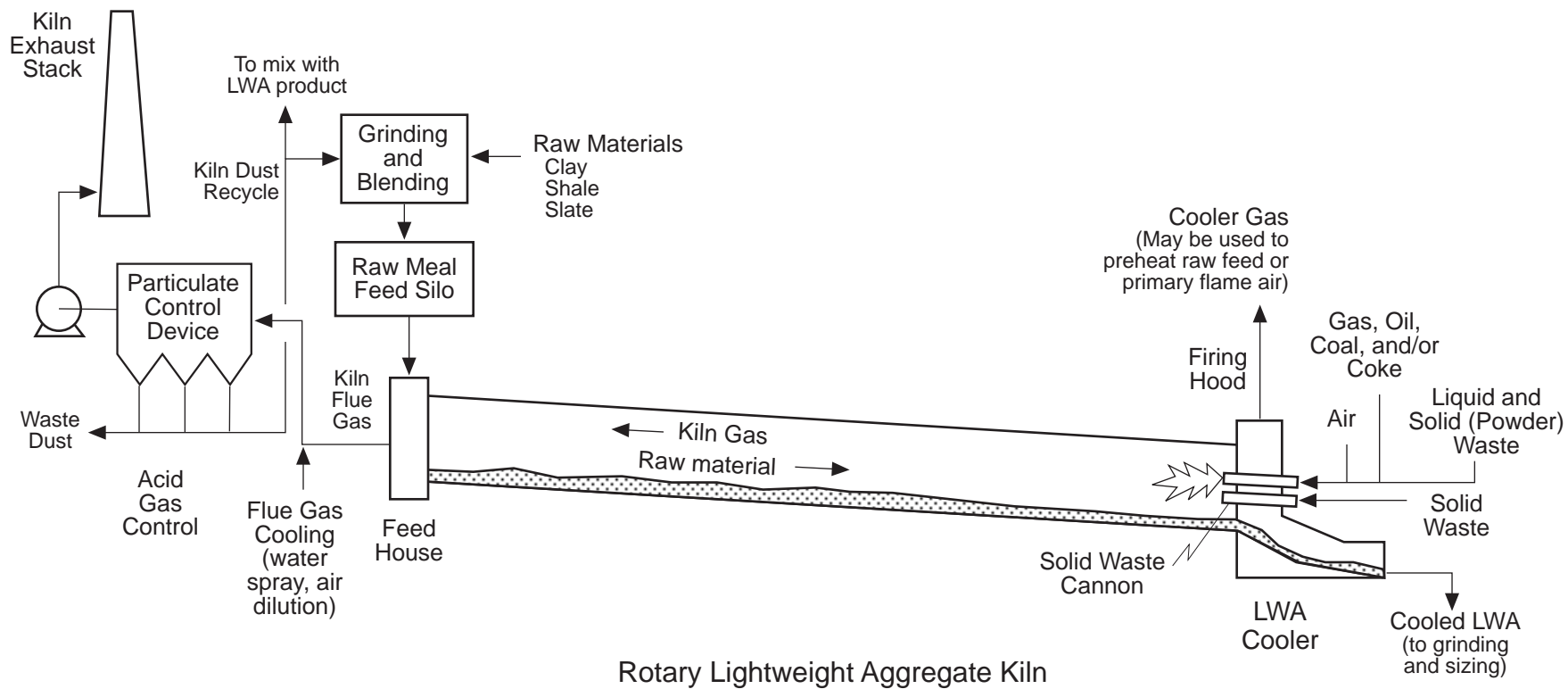


Figure 2-15. Lightweight aggregate kiln.

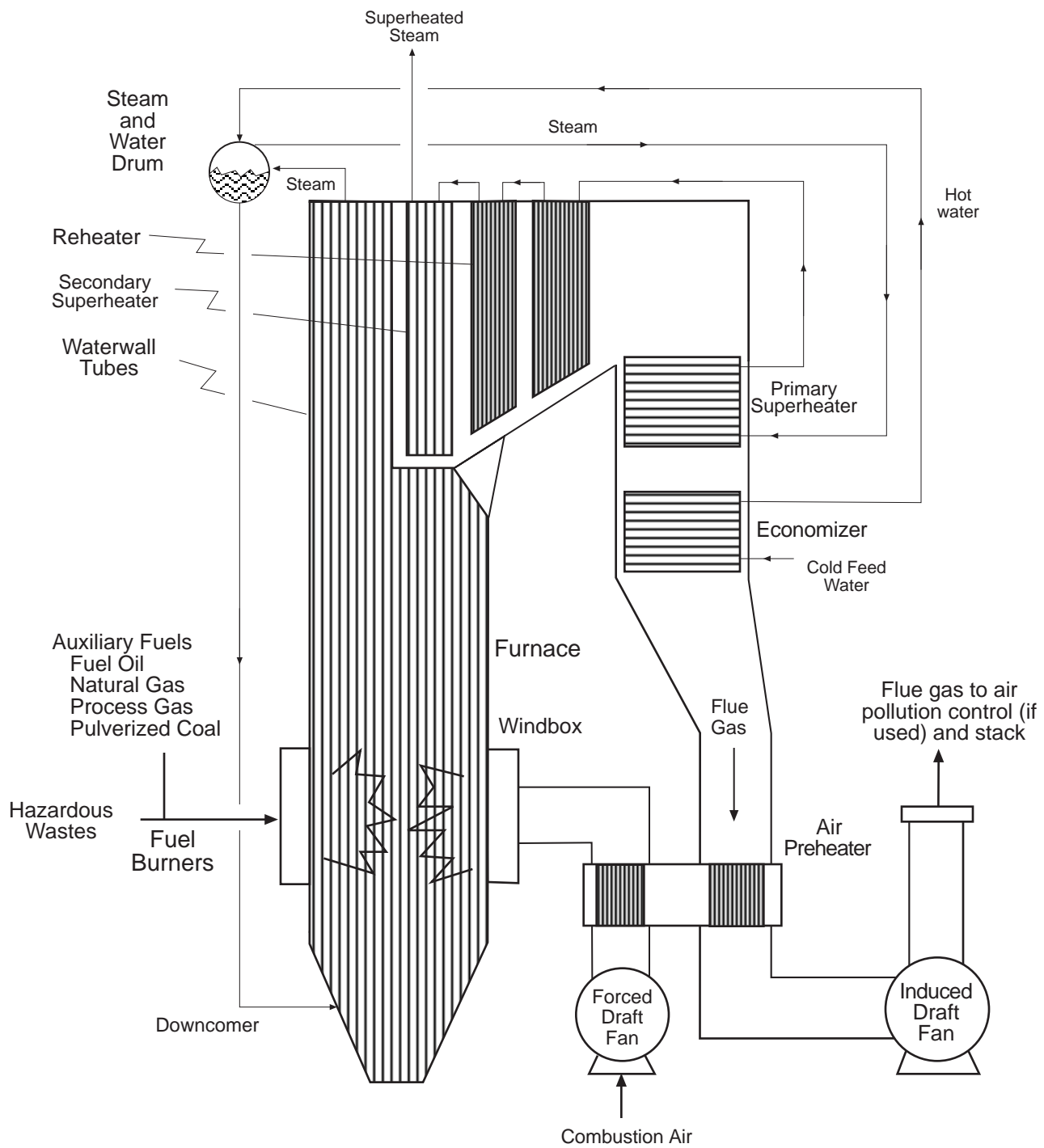


Figure 2-16. Watertube boiler.

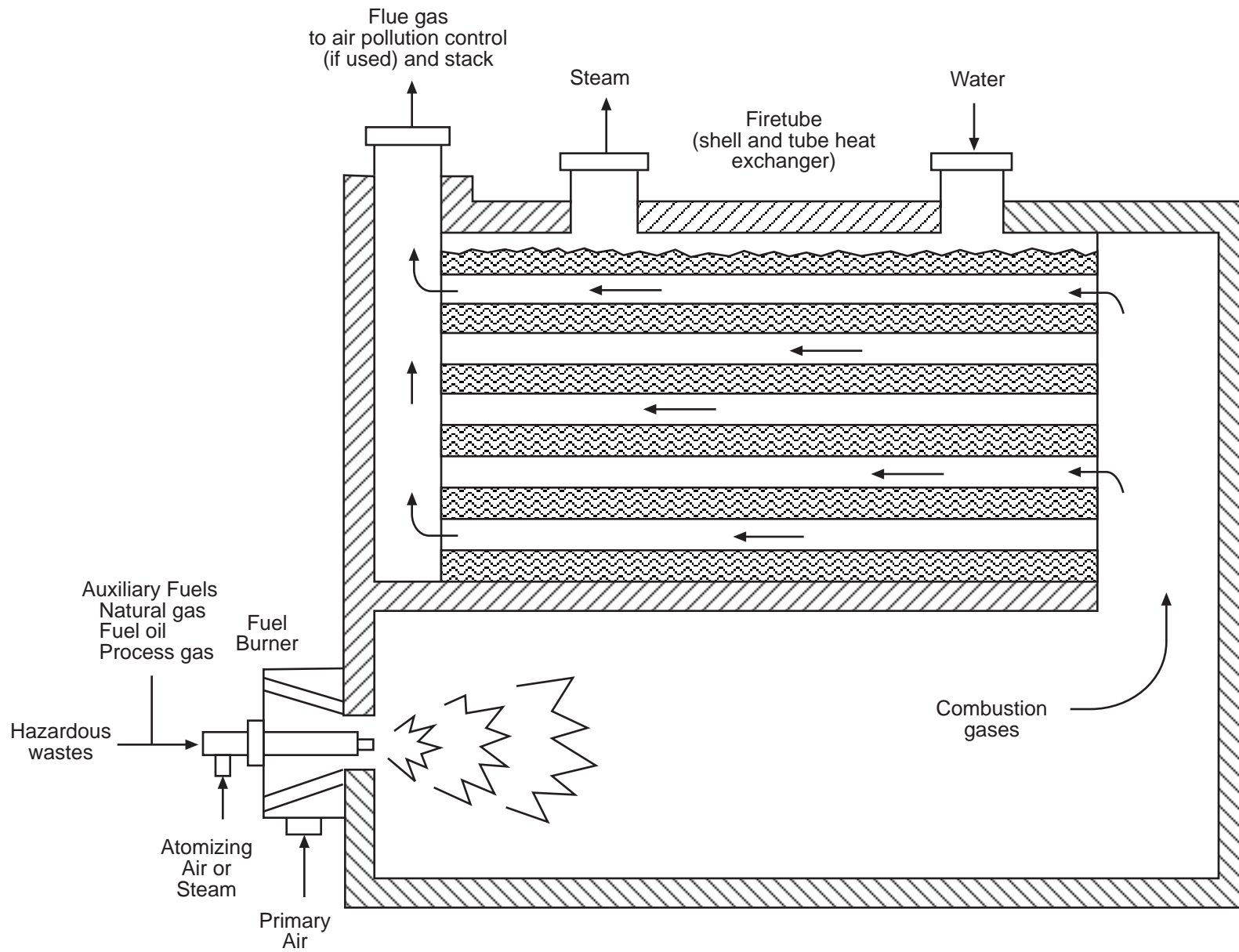


Figure 2-17. Firetube boiler.

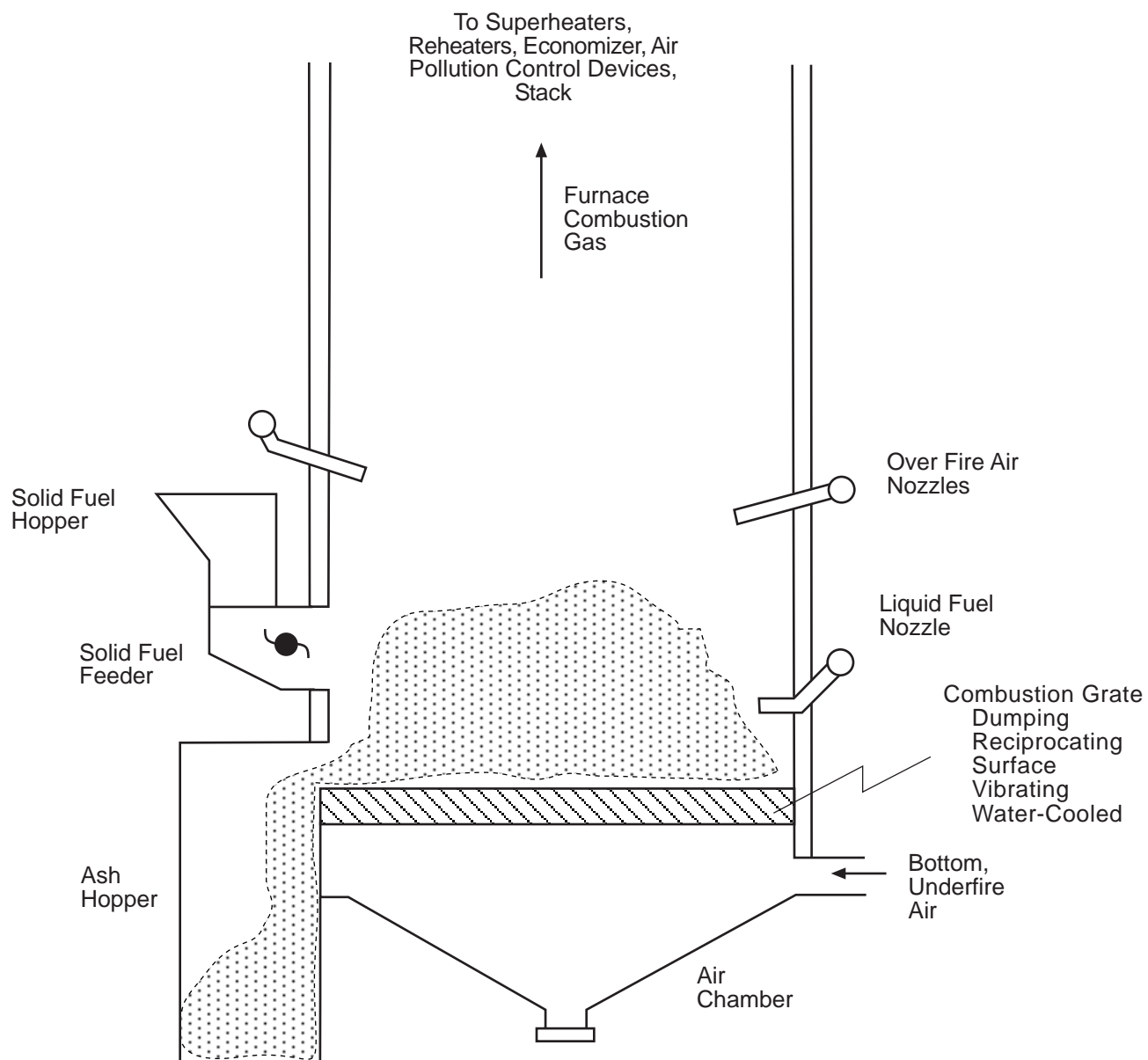


Figure 2-18. Spreader stoker boiler.

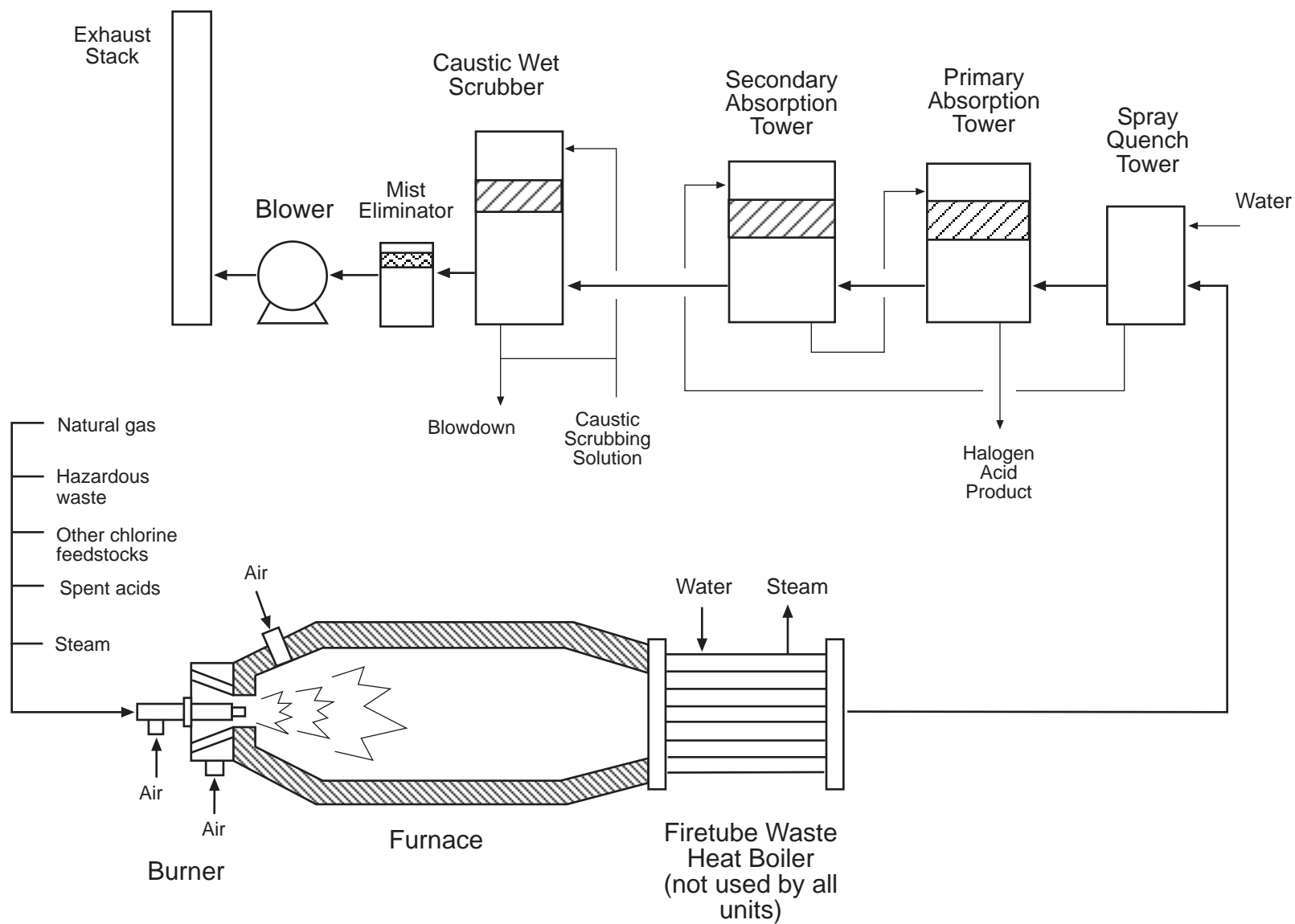


Figure 2-19. Halogen acid recovery furnace.

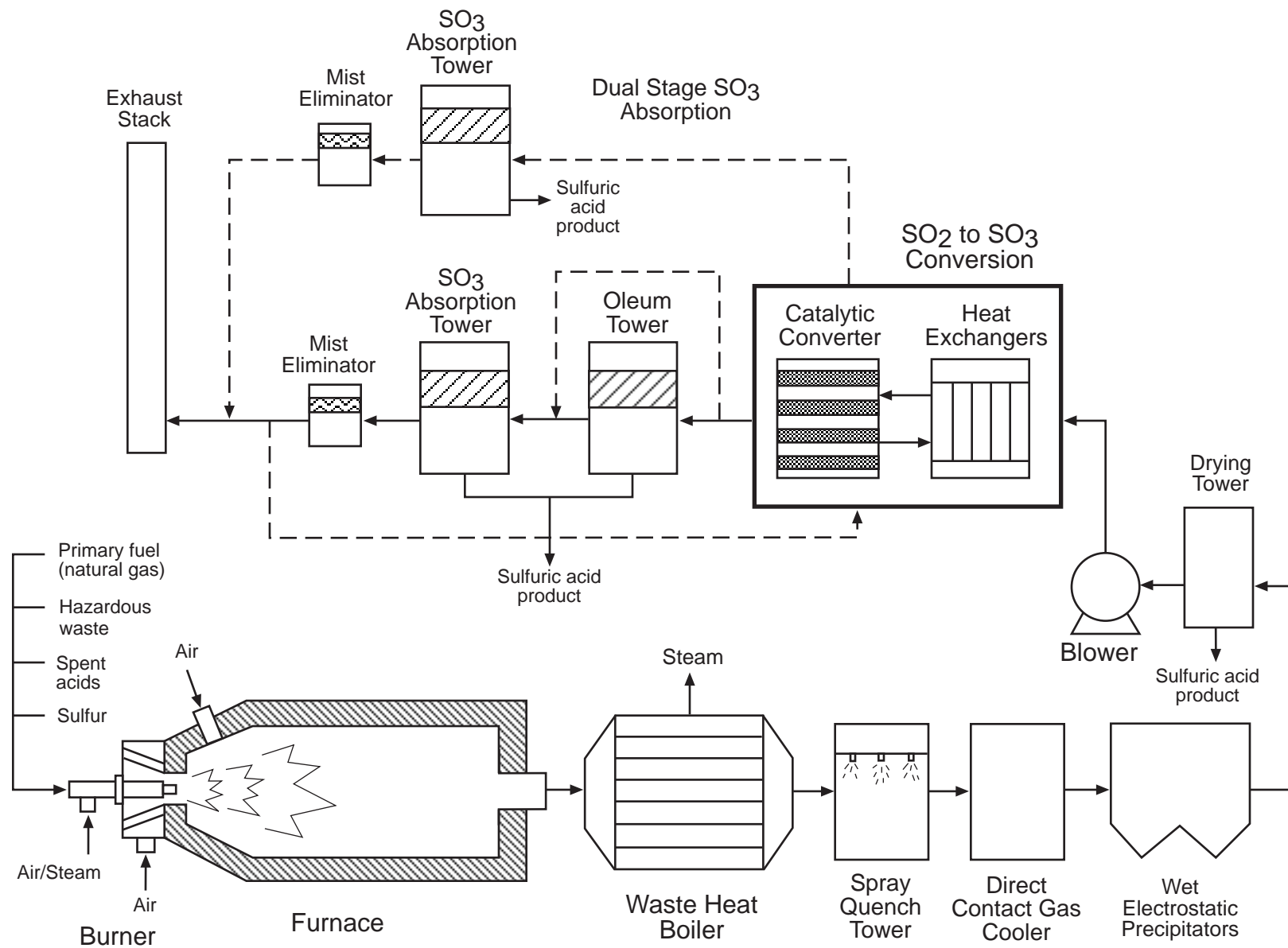


Figure 2-20. Sulfuric acid recovery furnace.